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ESTIMATING LEACHATE PRODUCTION FROM CLOSED HAZARDOUS WASTE LANDFILLS

by

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Interagency Agreement No. DW89007401

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Specific yield was determined for two data sets: One collected by a commercial hazardous waste site operator and provided by the U.S. Environmental Protection Agnecy, and the other collected by the authors at a hazardous waste site located in New York State. An automatic data logger with ASCII and voice transmission of data by phone lines was used to collect hourly measurements of leachate level at the latter site.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs, and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local government, and the needs of both large and small businesses in handling their wastes responsibly and economically.

This document presents analytical methods for estimating leachate production at closed hazardous waste landfills. Hypothetical landfills are described and leachate production is estimated using these analytical methods. Leachate production data obtained from two closed hazardous waste sites are also analyzed to determine typical specific yield values for mixed waste. Finally, physical models of mixed waste were constructed and drained to determine leachate production for selected waste configurations.

The intended audience for this document includes those involved in preparing, reviewing and approving permit applications for hazardous waste landfills.

Thomas R. Hauser
Director
Hazardous Waste Engineering
Research Laboratory

CONTENTS

Foreword iii
Abstract iv
Figures. vi
Tables viii

1. Introduction 1
2. Conclusions and Recommendations 3
3. Theory of Saturated/Unsaturated Fluid Flow. 5
   Equations of Fluid Flow. 5
   Transport and Storage of Water in the Soil 9
4. Data Availability and Model Selection 12
   Data Requirements. 12
   Sources of Data. 12
   Data Availability. 13
   Conceptual Model Availability. 13
   Summary of Models. 25
5. Estimation of Drainage Rates (Leachate Flux) from Closed Landfills 27
   Major Components of the Methodology. 27
   Guidelines for Decision Making and Parameter Estimation. . 29
   Example Cases. 31
6. Application of Specific Yield to Leachate Production. 47
   Specific Yield Analysis for the Commercial Site. 48
   Specific Yield Analysis for Glen Falls, New York 52
   Specific Yield Analysis for the Physical Models. 60

References 71
Appendices

A. Cell Volume Calculations 75
B. Soil Characterization Data. 79

FIGURES

Number		Page
3.1	Typical installations for measuring soil water pressure under saturated and partially saturated conditions	6
3.2	Typical relationship of hydraulic conductivity to soil water content for sand, loam, and clay	8
3.3	Typical water retention relationships for sand, loam, and clay	9
4.1	Typical hazardous waste landfill for drum disposal	16
4.2	Moisture content profile during drainage to a shallow water table	19
4.3	Properties of Yolo light clay	21
4.4	Water content profiles in Yolo light clay during drainage	22
4.5	Comparison of drainage rates from Yolo light clay using unit gradient (analytical) analysis and finite difference (numerical) analysis	23
4.6	Areal view of typical drum packing	24
4.7	Ranges of specific yield for various geologic materials	25
5.1	Decision tree analysis to determine leachate production from closed landfills	28
5.2	Analysis process for Example Case 1	33
5.3	Leachate Production for Example Case 1	36
5.4	Analysis process for Example Case 2	38
5.5	Predicted leachate production and level for Example Case 2	40
5.6	Analysis process for Example Case 3	41
5.7	Predicted leachate production and level for Example Case 3	43
5.8	Analysis process for Example Case 4	44

Number		Page
5.9	Idealized water content profile at time of closure for Example Case 4	45
6.1	Plan view of Cell	48
6.2	End view of waste site at Glen Falls, New York	53
6.3	Leachate level measurement system.	54
6.4	Leachate levels in hazardous waste site at Glen Falls, New York	55
6.5	Leachate levels during pumping of waste site at Glen Falls, New York	56
6.6	Comparison of leachate levels to atmospheric pressure.	58
6.7	Diagram of physical model treatments	61
6.8	Data collection system for drainage studies.	62
6.9	Water retention in loamy sand and sand	66
6.10	Comparison of the effect of barrels on cumulative drainage rates in sand	66
6.11	Comparison of the effects of barrel layering on cumulative drainage in sand	67
6.12	Comparison of the effects of voids on cumulative drainage in vertically arranged barrels in sand	67
6.13	Comparison of effects of voids on cumulative drainage in horizontally arranged barrels in sand	68
6.14	Comparison of effects of voids on cumulative drainage in horizontally arranged barrels in loamy sand	68
A.1	Schematic of typical subcell construction.	77
B.1	Particle size distribution for soils used in this study.	79
B.2	Water retention for soils used in this study.	80

TABLES

Number		Page
4.1	Reported hydraulic and geotechnical properties of hazardous wastes	14
4.2	Summary of conceptual models	26
6.1	Monthly maximum leachate level and volume from pumped subcells of the cell	50
6.2	Drainage test configuration and descriptions	60
6.3	Treatment summary information	64
A.1	Leachate data from cell - monthly maximum leachate level	76
B.1	Particle size distribution for soils used in this study	79

SECTION 1

INTRODUCTION

Hazardous waste landfills operating in humid areas currently generate significant quantities of leachate. This leachate collects on top of the liner and is pumped or drained by gravity via leachate collection systems. Under the present Resource Conservation and Recovery Act (RCRA) regulations. the level of leachate standing on the liner should not exceed 1 ft (approximately 30 cm). However, two studies (Skinner 1981; Montaque 1982) have shown leachate levels in hazardous waste landfills as great as 6 m. Considerable effort has been expended to reduce these levels; however, the results have been less than desirable. Skinner (1981) reports that clogged leachate collection systems, cover leakage, and waste settlement have all added to the difficulty of draining some facilities.

After a landfill has been closed, fluid input to the waste should be greatly reduced by the low hydraulic conductivity of the cover materials generally used. If leachate in the cell lies above the 30-cm standing level specified by RCRA regulations, operators will be required to pump or drain the cell untill it can be demonstrated that the guideline level has been achieved. Should the cover or liner function improperly, additional fluid may be introduced to the landfill. If techniques can be developed to estimate the fluid drainage rate from a properly functioning closed landfill, deviations from the predicted leachate drainage rate may be used as indicators of cover or liner performance. It is the intent of this document to present suitable analytical methods for predicting the flow of leachate to underdrains from closed hazardous waste landfills.

There were three major objectives for this project. The first was to estimate the magnitude of leachate production from a closed hazardous waste landfill. These estimates were used to provide initial input data for the study and allow the study to proceed in a rational and scientific manner. To estimate leachate production, this phase of the project was divided into two subtasks. In the first subtask, a review of the existing data on the hydraulic properties of waste materials was undertaken. In the second subtask, a review of existing conceptual models was completed to determine the applicability of these models to predict drainage of fluid from landfills. From this review, several models for simulating landfill drainage were selected based on three criteria: 1) the model should represent the physical phenomena of drainage in waste material, 2) the model should have limited input data requirements, and 3) the model must be easy to use.

Finally, the two subtasks were combined to estimate leachate production from four scenarios of landfill design and performance. These example cases provide insight into each model's applicability.

The second major objective of the study was to locate and gain access to a closed hazardous waste landfill to conduct field research in order to evaluate the models selected as part of the first objective. To accomplish the second objective, landfill operators and regulatory agencies were contacted to determine their willingness to cooperate in field studies and the availability of data that could be input to the models.

If it appeared that only limited data were available, then the third major objective was to evaluate the effect of barrel arrangement, void volume, and soil type on drainage using a physical model.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Two major approaches to determine the leachate production from a hazardous waste landfill are presented in this report. First is the use of models which utilize the theory of fluid transport in soil to describe leachate production. It is readily apparent that numerical and analytical models are either too complex or require currently unavailable characterization data. Even the application of the specific yield model requires generally unavailable information about the volumes of drainable large voids, specific yield or water retention, and hydraulic conductivity values for the backfill material and the volume of nondraining solids.

The second approach is to use specific yield estimates from a similar waste site. Very few values of specific yield have been reported for either nonhazardous or hazardous waste sites. Estimates of specific yield can be determined from single withdrawals of leachate from a waste site if care is taken to account for possible infiltration of precipitation or changes in barometric pressure during measurements of leachate levels. It is highly recommended that leachate levels be monitored with an automatic data collection system for several days before and after each leachate withdrawal. The data collection system should also record barometeric pressure, temperature, and precipitation data.

The effect of barrel arrangement, void volume, and soil type on specific yield were examined in a physical model. Values of specific yield were shown to be most sensitive to the presence of large voids. The effects of soil texture on drainage rates and specific yield were also observed: fine soil retained more water and had lower drainage rates. The presence of nondraining solids generally reduced the drainage rate.

It is apparent from the lack of useful information currently available on existing hazardous waste sites that a protocol should be established that requires the careful characterization of waste sites as they are built. Because site failure is always a possibility, site characterization information describing all aspects of waste form, placement, and burial must be part of the site history. Only if this information is available can reasonable predictions of leachate production be made without extensive assumptions or potentially dangerous site characterization investigations to estimate the specific yield of the hazardous waste site under study. A new research effort should be initiated to define acceptable construction and

as-built reporting criteria for all new waste site construction. Once the reporting criteria are established, procedures for prediction of leachate production can be developed for use by landfill operators.

SECTION 3

THEORY OF SATURATED/UNSATURATED FLUID FLOW

In this section, a brief review of the theory of fluid flow in porous media is outlined to provide the essential concepts and definitions of terms required for the subsequent discussion and analysis of flow in porous media. For further background on the subject, the reader is referred to the cited literature (Bear 1972; Klute and Heermann 1978).

EQUATIONS OF FLUID FLOW

Water movement in porous media can occur in the liquid phase or gas phase. In a water saturated system, the water transport is solely in the liquid phase and is a process of convective transport driven by mechanical forces (Klute and Heermann 1978). These forces are given by the negative gradient of a potential function. A commonly used potential function is the energy per unit weight of soil water or the hydraulic head, H. The hydraulic head is the sum of two components, the gravitational head, Z, and the pressure head, h. The gravitational head of the soil water at a point in the soil is the elevation of that point above an arbitrarily chosen datum and is a measure of the gravitational potential energy per unit weight of the soil water. In porous media, the pressure head, h is related to the pressure in the soil water by the relationship:

$$h = \frac{P_w - P_{atm}}{\rho g} \tag{3.1}$$

where h is the pressure head [L], ρ is the soil water density [M/L^3], g is the acceleration from gravity [L/t^2], P_w is the pressure of the soil water [$M/L \cdot t^2$], and P_{atm} is the atmospheric pressure [$M/L \cdot t^2$]. For most groundwater flow, the atmospheric pressure is taken to be zero. The hydraulic head and its components may be measured in those cases where P_w is greater than P_{atm} with a piezometer (a cased well of small diameter, terminated at the point in the soil at which the head is to be measured). Figure 3.1. shows a piezometer and the interpretation from it of the hydraulic head and its components (Klute and Heermann 1978).

In partially saturated soils, the pressure in the liquid phase, P_w, is usually less than atmospheric, and the piezometer cannot be used to measure the hydraulic head. A tensiometer is used to extend the measurement of hydraulic head to partially saturated soils. A tensiometer consists of a porous ceramic cup cemented to a rigid plastic tube capped with a filler

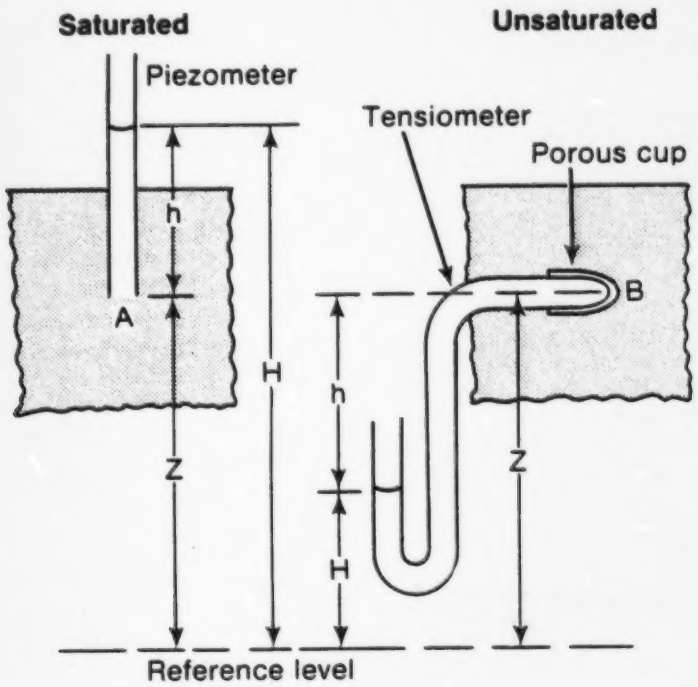


Figure 3.1. Typical installations for measuring soil water pressure under saturated and partially saturated conditions (H = hydraulic head, h = pressure head, and Z = gravitational head).

plug and small-diameter tubing leading to a manometer, terminating in a reservoir of mercury. Except for the reservoir and the portion of the small-diameter tubing filled with mercury, the internal volume of the system is completely filled with water. When properly emplaced in the soil, the pores in the ceramic cup form a continuum with the pores in the soil. Water moves either into or out of the tensiometer system until an equilibrium is attained across the ceramic cup. The mercury level in the manometer tubing adjusts correspondingly (Wilson 1982). The pressure head in partially saturated media is often referred to as the capillary pressure head because it reflects the capillary forces acting on the fluid. Figure 3.1 shows the typical design of the tensiometer.

The equation of soil water movement is developed by combining a mass balance for the soil water with the flux equation. The mass balance equation relates the time rate of change of water content of a differential volume element of soil to the difference of inflow and outflow from the elemental volume and to the time rate of production/destruction of soil water within the element. If it is assumed that the soil water is of constant density, the mass balance may be written as a volume balance. In one-dimensional form; the volumetric balance equation may be written as

$$\frac{\partial \theta}{\partial t} = \frac{-\partial(q)}{\partial z} + S \qquad (3.2)$$

where θ is the volumetric water content [L^3/L^3], z is the vertical coordinate [L] taken as positive downward, t is time, q is the soil water flux [L/t], and S is a source term [1/t]. The latter may be used to represent the extraction of water from soils by plant roots.

The soil water flux term (q) in Equation 3.2 is assumed to be given by Darcy's equation, which is the product of the hydraulic conductivity, K, and the negative gradient of the hydraulic head, dH/dz. For a saturated soil, the hydraulic conductivity is generally taken to be a constant. As the water content of the soil decreases, however, the ability of the soil to transmit fluid decreases very rapidly. Darcy's equation has been extended to unsaturated soils by considering the conductivity to be a function of the water content of the soil (Buckingham 1907). Figure 3.2 shows the typical relationships of hydraulic conductivity to soil water content for several soil groups. The primary reasons for the decrease in K as θ decreases are 1) the effective cross section of the soil that is available for liquid flow is decreased, 2) the drainage of water from the larger pores that contribute strongly to the conductivity, and 3) the tortuosity of the the fluid flow path is increased.

In one dimension, the soil water flux term may be written from Darcy's Law as

$$q = -K(\theta) \frac{\partial H}{\partial z} \qquad (3.3)$$

where $K(\theta)$ is the hydraulic conductivity as a function of the water content. The algebraic sign of the flux indicates the direction of the flow with respect to the chosen coordinate axis. Because the hydraulic head is the sum of the pressure and gravitational heads, Equation 3.3 may be rewritten as

$$q = K(\theta) \left(\frac{\partial h}{dZ} + 1\right) \qquad (3.4)$$

Substituting Equation 3.4 into the mass balance equation given by Equation 3.2 yields the following:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \; K(\theta) \left(\frac{\partial h}{\partial Z} + 1\right) + S \qquad (3.5)$$

Equation 3.5 is a partial differential equation in two dependent variables, θ and h. To obtain an equation for water flow in one dependent variable, another relationship between θ and h is required. This relationship is known as the water retention function or water release curve. In

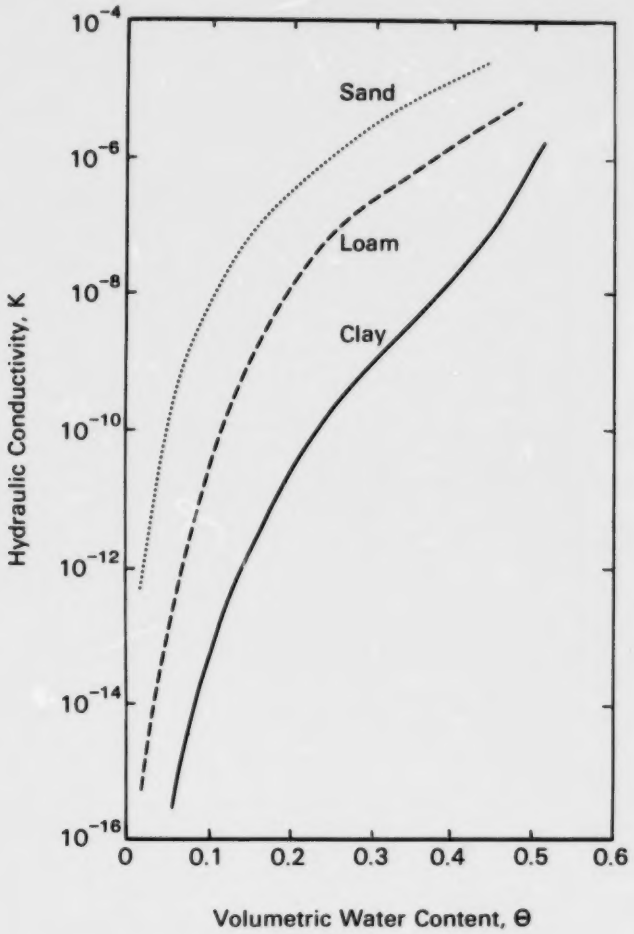


Figure 3.2. Typical relationship of hydraulic conductivity to soil water content for sand, loam, and clay (after Hillel 1977).

general, the water content decreases as the pressure head decreases. The retention function displays a phenomenon called hysteresis; that is, the water content at a given pressure head depends on the historical sequence of wetting and drying that has been imposed on the soil. If the flow process is entirely one of drainage or of wetting from a given initial water content, the relation between θ and h can be taken as single-valued and non-hysteretic. Figure 3.3 shows typical water retention data for several soil groups. If, however, the flow process involves sequences of wetting and drying, the water retention function is multivalued and highly hysteretic. There are an infinite number of possible $\theta(h)$ relationships or scanning curves lying between the main drying curve and main wetting curve. In non-hysteretic flow, the functional form of $\theta(h)$ is single-valued and may be easily represented by empirical formulae. Hysteretic flow is much more

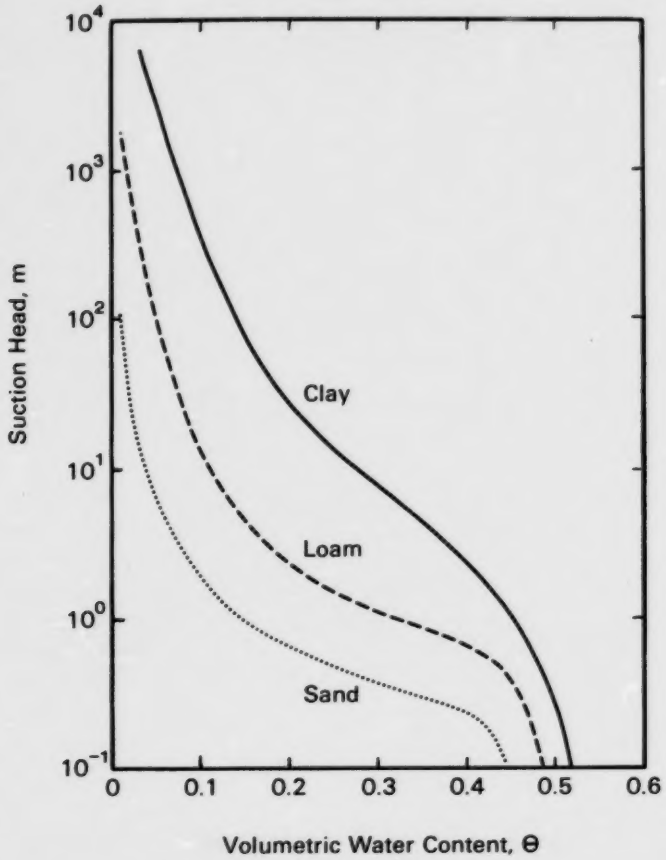


Figure 3.3. Typical water retention relationships for sand, loam, and clay (after Hillel 1977).

complicated since a method must be devised to keep account of the necessary reversal points and select the appropriate scanning curve.

In contrast to the water retention relationship, the relationship between hydraulic conductivity and water content has been found to be only slightly hysteretic. In many cases, the hysteresis in $K(\theta)$ is hidden within the uncertainty of the experimental data. For the purpose of the analysis described in this report, $K(\theta)$ is assumed not to be hysteretic.

TRANSPORT AND STORAGE OF WATER IN THE SOIL

Water enters deep soil storage by infiltration from soil surface storage, upward flow from a water table, and lateral transport. Water is lost from storage by evaporation, deep percolation, transpiration, and lateral transport. Water is transferred from one place to another in storage by redistribution and evaporation/condensation. It is convenient to consider these processes separately and reserve the special names for the various

processes, but in terms of modeling the behavior of the soil moisture system, all aspects of transport into, within, and out of the soil are governed by Equation 3.5. No distinctions need to be made in the water flow models between infiltration and redistribution. The flux is simply determined by the direction of the potential gradient and the hydraulic conductivity of the soil.

The terms field capacity and permanent wilting point (Daubenmire 1959) have long been used to describe the upper and lower limits of soil moisture in the soil. Field capacity is used to denote the water content of soil when the rate of change of water content in the profile becomes insignificantly low following a rain or irrigation. The permanent wilting point is the water content of the soil below which water cannot be extracted by plants. The difference in water content between field capacity and permanent wilting point multiplied by the depth of the soil is the water-holding capacity of the soil reservoir. The difference between the saturated water content and the field capacity is the specific yield.

The permanent wilting point of soil is often correlated with a fixed, low, water pressure head. Plants that adapt to drought and reduce transpiration rates to values near zero can withdraw water from the soil at water potential near the lowest daytime water potentials of the leaves. Permanent wilting point is taken as the water content of the soil at -15,000 cm of soil water head. In arid regions, certain plants (cactus, sagebrush, and other desert plants) have adapted to dry soil conditions and either do not exhibit wilting or osmotically adjust their leaf water potential so that wilting does not occur except at very low water potential (-30,000 to -50,000 cm or lower). However, soil water retention characteristics are such that the water contents for most medium- and coarse-textured soils change little between -15,000 and -50,000 cm so that the water content at -15,000 cm is generally a reasonable estimate of the permanent wilting point.

Field capacity is much more difficult to define. In the past, correlations have indicated that the water content at 333 cm (1/3 bar) of soil water pressure head could be used as estimates of field capacity (Hausenbuiller 1972). However, field capacity is a dynamic condition of drainage, hence is a function of the hydraulic conductivity of the profile rather than the water potential of the soil. Therefore, it is only by coincidence that any set potential can be used to estimate field capacity. Field capacity is also a function of the arbitrary choice of a negligible drainage rate. A reasonable negligible rate might be 10% of the actual evapotranspiration rate (Campbell and Harris 1981). Typical midsummer evapotranspiration rates vary from 1 to 5 mm/day. Under dry conditions, evapotranspiration may be 1 mm/day or less. A reasonable field capacity water content under these conditions would be a profile water content associated with a drainage rate of 0.1 mm/day.

Estimates of field capacity can be made if the hydraulic conductivity function of the soil profile is known. Gardner (1970) showed that the rate of change of water content in an initially wet, deep soil profile is equal to the hydraulic conductivity of the profile. This relationship, which

appears to hold for relatively uniform soil profiles, allows one to make direct field measurements of the hydraulic conductivity. Measured conductivity-profile water content relationships can then be used to define field capacity in quantitative terms. The water content at which the drainage rate or hydraulic conductivity is 0.1 mm/day can be used to define field capacity of a uniform soil profile. The concepts of unsaturated water flow just discussed, including negative water potential (capillary head), unsaturated conductivity, and field capacity are basic to an understanding of drainage and leachate production in closed landfills. The ability to predict drainage times and to systematically model the leachate production depends on how well the overall system can be characterized hydrologically and how well the actual system conforms to the simplified initial and boundary conditions used to describe the drainage. Provided that the systems conform to the assumptions of the models presented, field data describing the hydraulic properties of the waste are crucial if justifiable predictions about leachate production are to be made.

In the following sections, an analysis of leachate production from closed landfills is presented. The theoretical background and technology discussed in this section is sufficient for the conceptual understanding of these models. The reader is cautioned, however, that any model, no matter its level of simplicity, can only be applied properly if the user understands the fundamental limitations and assumptions inherent in the model. The models presented in the following sections represent a simplified approach to predicting leachate production from closed landfills. Their use in any other context without field verification should not be attempted.

SECTION 4

DATA AVAILABILITY AND MODEL SELECTION

The objective of this phase of the effort was to assess the availability of data concerning the hydraulic properties of waste and backfill material, to review the conceptual models applicable to study the drainage characteristics of wastes and soil in a landfill environment, and to select an appropriate conceptual model to estimate leachate production from typical hazardous waste sites.

DATA REQUIREMENTS

To model the flow of water through landfill wastes and soil, several types of data are necessary. Data are needed for the physical packing and disposal techniques practiced in hazardous waste cells. In most landfill scenarios, liquid flows through saturated and partially saturated media. To represent these types of flow, data concerning the saturated hydraulic conductivity, porosity, and the effects of desaturation on the capillary pressure and hydraulic conductivity are required. In addition, landfilled material may also deform and consolidate. Geotechnical data must be used to determine the effects of loading and consolidation on the saturated void ratio and saturated hydraulic conductivity.

SOURCES OF DATA

Study of the hydraulic properties of wastes and soil drainage encompasses a wide range of disciplines, such as chemical, civil, agricultural, and geotechnical engineering, biology, geology, soil physics, and soil chemistry. A comprehensive literature review was undertaken using computer-assisted data bases. The data bases surveyed included NTIS (for government research reports), COMPENDEX (for engineering documents), and BIOSIS (for biological and environmental publications). Key words, such as landfill, drainage, landfill cells, liner, leachate, conductivity, and permeability were used to identify titles and abstracts applicable to this study. In addition, owners and operators of hazardous waste landfills were contacted to determine their disposal techniques and types of waste forms handled at the facility.

DATA AVAILABILITY

Hazardous wastes are usually disposed of in landfilled cells in two forms: Large, solid materials containing hazardous waste (such as drums or barrels), or contaminated bulk materials (such as soils and sludges). Methods for disposing of drums vary considerably. Barrels can be stood on end, laid on their side, or placed randomly in the waste site. The number of barrel layers in each lift varies. During lift construction, soil backfill is often placed on and around the drums as an intermediate cover to provide support for truck and heavy equipment movement. Other contaminated containers are disposed of in a less orderly fashion because of irregularities of size and shape. In addition to soil backfill, contaminated soil and/or bulk waste may be used as an intermediate cover. In the second form of landfill disposal, bulk waste and contaminated soil may be disposed of within the cell. As in municipal waste disposal, wastes are spread and compacted into lifts using various types of heavy construction equipment.

Flow through these various types of landfills is markedly different. At drum disposal sites, the drum packing density and the efficiency of backfilling between the drums strongly influence both the flow and storage of fluids within the cell. In bulk or soil sites, drainage rates depend on the saturated and partially saturated hydraulic conductivity of the wastes.

Based on the literature survey, data concerning the saturated hydraulic properties of bulk waste were found to be quite limited. Data on the partially saturated properties [$\theta(h)$ and $K(\theta)$ relations] are almost entirely lacking. Data concerning the consolidation properties of waste materials are available in the geotechnical literature but only for several waste forms. More data on possible backfill soils are available in each of the categories discussed above. Waste forms receiving significant attention have been primarily municipal refuse and mine tailings. No data concerning the hydraulic properties of drum disposal sites were found during the literature review. Table 4.1 summarizes the data collected on hydraulic and consolidation properties of bulk waste materials obtained from the available literature.

CONCEPTUAL MODEL AVAILABILITY

Assumptions

Research efforts studying the flow of fluid through landfilled material have been conducted in both laboratory and field-scale experiments as well as theoretical studies. In all of the studies, simplifying assumptions were necessary about the complexity of the flow in order to model the landfill's behavior. The two most important assumptions made for this analysis were 1) the consideration that all liquid flow is vertical and 2) the hydraulic properties of the waste materials are uniform throughout the landfill. The rationale and implications of these assumptions are discussed below.

TABLE 4.1. REPORTED HYDRAULIC AND GEOTECHNICAL PROPERTIES OF HAZARDOUS WASTES

Waste type	Saturated parameters: K_{SAT} (cm/s)	Saturated parameters: Porosity	Saturated parameters: Compacted density (kg/m³)	Partially saturated parameters: K(θ)	Partially saturated parameters: θ(H)	Partially saturated parameters: θRES	Partially saturated parameters: Field Capacity	Grain size data	Consolidation parameters: C_v (cm²/s)	Consolidation parameters: E(σ)	Consolidation parameters: % Vol reduction	Shear strength data	Source
Municipal waste		50%					45%						Leckie et al. 1979
Municipal waste			340.0				10-14%						Rovers and Farquar 1973
Papermill sludge	1.0×10^{-4} 1.0×10^{-8}												Anderslund and Laza 1972
Flue Gas Desulfurization (FGD) sludge	1.0×10^{-4} 1.0×10^{-6}									X		X	Hagerty and Ullrich 1977
Solvay soda ash sludge			2.71*					X	2.87#	X		X	Kulhawy et al. 1978
FGD sludge		46-57%	1040-1280					X		X		X	Cunningham et al. 1977
Municipal waste							20-35%			X			Zimmerman et al. 1977
FGD sludge	1.0×10^{-2} 1.0×10^{-5}		2.72-2.52*						0.75-1.05#			X	Bond 1980
Lead/zinc mill tailings	3.4×10^{-6} 5.0×10^{-5}	41-57%	2.88-3.02*					X					Hardcastle et al. 1977
Uranium mill tailings	2.2×10^{-4}	44%	1.63**										Nelson et al. 1983
Municipal waste				X	X		30-40%						Straub and Lynch 1982
Uranium mill tailings													Klute and Heermann 1978
Coarse	6.3×10^{-3}	43.3%	1.48-1.57**	X	X	7.6%		X					
Medium	2.3×10^{-3}	45.8%	1.28-1.50**	X	X	9.0%		X					
Fine	6.7×10^{-7}	66.0%	0.90-1.10**	X	X	31.0%		X					
Fly ash	8.3×10^{-3} 5.0×10^{-2}		0.99-1.50**	X X	X X								Bond 1980
Municipal waste							Bulk density versus field capacity data						Fungaroli 1971
Municipal waste			287.0				28.6%						Remson et al. 1968
Spent oil shale										X		X	Pilz and Nelson 1982
Municipal incinerator residue	$4.1 \text{–} 6.9 \times 10^{-5}$												Maynard 1977
Phosphate tailings	1.2×10^{-4} 2.0×10^{-5}												Vick 1977
Coal mine wastes	1.4×10^{-3} 7.22×10^{-5}												Cowherd 1977
Waste clays from phosphate mining	1.0×10^{-4} 1.0×10^{-8}								$1.0\text{–}6.0 \times 10^{-4}$				Keshian et al. 1977
Fly ash/soil mixture	1.0×10^{-3} 1.5×10^{-6}												Parker et al. 1977
Red mud (aluminum tailings)	$1.2 \text{–} 20 \times 10^{-7}$								$0.09\text{–}6.9 \times 10^{-2}$				Somogyl and Gray 1977

* - particle density
\# - compression index
** - bulk density
X - data not readily available

The first important simplifying assumption made in this phase of the study was the reduction of the flow geometry from three dimensions to a one-dimensional analysis. Although landfills are three dimensional in nature, the assumption of flow only in the vertical direction may be valid for landfills of regular geometry receiving uniform areal recharge. The assumption may not be valid in landfills where surface soils (covers or daily backfill) or surface slopes result in increased runoff in certain areas of the landfill and ponding of precipitation in others. In addition, horizontal hydraulic gradients at the landfill sidewalls or the presence of a shallow water table may produce significant components of horizontal flow.

For modeling landfills complying with the RCRA regulations, assuming purely vertical flow within the landfill appears to be reasonable. It is expected that sidewalls and liners will be designed to minimize or eliminate horizontal movement of leachate to the surrounding soils. In addition, covers will be designed to maximize runoff and minimize infiltration. Highly permeable drainage layers at the bottom of landfills will result in horizontal flow predominantly within the drainage layer, while fluid flow above the drainage layer will remain essentially vertical.

In the second important assumption, effects of waste heterogeneity are ignored. Typical hazardous waste landfills currently in use in the United States handle a wide variety of solid wastes ranging from contaminated soils and sludges in bulk form to drummed waste and polychlorinated biphenol-contaminated transformers. In addition, soil material is often placed between the layers of drums to allow vehicle movement within the landfill cell during operation. Modes of deposition of the wastes range from neat upright stacking of drums and careful mapping of their location to haphazard disposal of drums and containers by dragline or overhead crane. Bulky waste material is often dumped and spread by bulldozer or front-end loader. In all cases, waste properties cannot be expected to be uniform throughout the landfill.

For this study, the focus is not on a complete description of fluid movement throughout the cell, but on that amount of fluid draining to the leachate collection system. The effect of the drainage collection system is to average the local drainage from various portions of the cell. In similar problems of agricultural drainage, Bressler and Dagan (1983) have suggested that simplified models of flow mechanisms can be employed because the details are lost in the process of averaging over large areas.

As a result of a review of the available research on flow in hazardous waste cells, two types of models were chosen for application. The first of these is a unit gradient approach (Sisson, Ferguson, and van Genuchten, 1980) and is applicable to soil or bulky waste cells (i.e., those cells receiving a uniform, soil-like waste stream). Such sites might be found at private generator/disposer sites when cells are used strictly for a specific kind of waste. An example of such waste would be flue gas desulfurizing sludge from a coal-fired electric utility plant. These types of waste would be expected to behave in a similar manner to soils and the drainage from these materials has been analyzed as such (Bond, Cole and Gutknecht 1982).

A specific yield model was chosen for use in drummed waste disposal cells where simple drainage is not expected. Figure 4.1 shows a cross section of a drum disposal landfill. As can be seen, backfill or cover soil has been placed between each layer of drums. The leachate in such a cell will fill the interdrum voids as well as the pore spaces of the soil backfill. During drainage of the cell, the most easily drained leachate is contained in the interdrum voids. In addition, disposal techniques currently in use will allow for most of the interdrum voids to be connected to some degree along each horizontal lift. Also, it is expected that some connection of the interdrum voids in the vertical plane will occur. Therefore, drum waste cells will drain to underdrain systems primarily through these rapidly draining, large voids and a secondary contribution of fluid will be received from intermediate soil covers. Perched water table conditions are also expected to exist in cell areas where the interdrum voids are not vertically connected. These perched areas will drain much more slowly because the drainage will be controlled by the conductivity of the backfilled soil. Abrupt drainage of these zones may also occur if settlement or degradation of the waste containers cause voids to open up and allows drainage of the perched zone to the underdrains. However, at this phase of the study the largest leachate volume is expected to come from the connected interdrum voids.

The following discussion outlines the unit gradient method for bulk waste cells and the specific yield method for drum or mixed-disposal cells to determine the drainage rate from one-dimensional landfill cells.

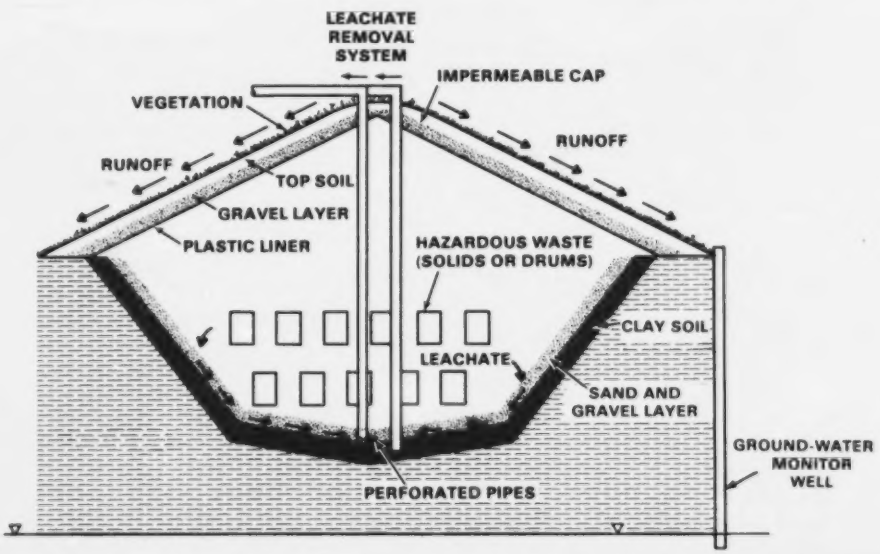


Figure 4.1. Typical hazardous waste landfill for drum disposal (after Skinner 1981).

Unit Gradient Technique - Bulk Waste Sites

The equation for predicting the one-dimensional flow of water in homogeneous porous media is given by

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z} \left(K(\theta) \frac{\partial H}{\partial Z} \right) \tag{4.1}$$

where θ is the volumetric water content [L^3/L^3], t is the time, Z is the depth (positive downward) [L], and H is the total hydraulic head (elevation head plus pressure head) [L].

$K(\theta)$ is the hydraulic conductivity [L/t], which may be represented as

$$K = f(\theta) \tag{4.2}$$

Numerous field studies (Simmons, Neilsen and Bigger 1979; Black, Gardner and Thurtell 1969) have been conducted to study the redistribution of water in a soil profile following irrigation. In general, these studies have found that when surface flux caused by evaporation is eliminated, the soil will drain such that the hydraulic gradient between any two points in the profile will approach unity. The gradient, $\partial H/\partial Z$, may be approximated as

$$\frac{\Delta H}{\Delta Z} = \frac{(Z_a + h_a) - (Z_b + h_b)}{(Z_a - Z_b)} = 1 \tag{4.3}$$

where Z is the elevation head at the points a and b and h is the pressure head at the points a and b.

The assumption of a unit hydraulic gradient indicates that the soil water pressure throughout the column is constant at any given time. Substitution of Equation 4.3 into Equation 4.1 yields the following:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z} (K(\theta)) = \frac{dK}{d\theta} \cdot \frac{\partial \theta}{\partial Z} \tag{4.4}$$

If the soil profile initially is taken to be at some uniform moisture content, θ_o, Equation 4.4 is constrained by the following initial condition:

$$\theta(Z, t = 0) = \theta_o \tag{4.5}$$

The initial value problem given by Equation 4.4, also known as a Cauchy or characteristic value problem, has been the subject of many studies in mathematical and engineering literature (Lax 1972; Aris and Amundson 1973). Equation 4.4 has been integrated by Sisson, Ferguson and van Genuchten (1980) to yield:

$$t = \frac{Z}{\left. \frac{dK}{d\theta} \right|_{\theta = \theta_i}} \tag{4.6}$$

where θ_i is the volumetric water content at the time of interest.

Equation 4.6 solves for the time required to drain a soil to a given water content, provided an expression for the hydraulic conductivity can be differentiated. At any given point in the column, Z, the solution consists of two drainage stages. The first stage is characterized by drainage at a constant water content until the time when the drying front has reached the fixed point, Z, in the column. This phase of drainage is termed stage one drainage and is characterized by a constant flux of fluid past the point in the column. Stage one drainage is calculated from Equation 4.6 by setting θ_i equal to the initial water content θ_0. The length of time necessary for stage one drainage is obtained by solving Equation 4.6 at the initial water content θ_0 and at the given depth of the column, Z.

The flux, q, past any point in the profile, Z, during this stage of drainage is given by solving Darcy's equation given the hydraulic gradient of -1:

$$q(Z,t) = K(\theta(Z,t)) \tag{4.7}$$

The second stage of drainage occurs as the water content at the given point in the column begins to decrease. The time needed to reach a specified water content at the point in the column is obtained by solving Equation 4.6 at the specified water content and depth prescribed.

As above, the flux during stage two drainage past any point in the profile can be calculated from the relationship between water content and hydraulic conductivity.

Effects of A Shallow Water Table

The theoretical analysis presented above assumes that the soil profile is deeply drained; that is, the water table is located at an infinite depth. This is necessary to maintain the condition of unit hydraulic gradient. In many studies, however, it is necessary to consider the effects of a water table condition at the bottom of the profile. During stage one drainage, the soil will drain in a similar fashion to the infinite profile presented by Sisson, Ferguson and van Genuchten (1980). As the drainage process passes into stage two, the column will feel the effects of the shallow water table. The soil column will not drain uniformly but instead will approach the static equilibrium water content profile determined by the capillary structure of the soil. The profile will be saturated at the bottom where it contacts the water table. Above the water table, the water content will decrease as the distance to the water table increases. The equilibrium moisture content of a soil is a function of the capillary pressure of the pore water:

$$\theta = f(h) \tag{4.8}$$

Numerous authors have determined relationships for the moisture content-capillary pressure function. Su and Brooks (1976) present a thorough review of the subject.

To simplify the problem, the profile can be divided into an upper and lower flow regime. In the upper flow regime, the profile is modeled using the unit gradient analysis presented earlier. The lower portion of the profile is considered in equilibrium with the water table. The upper part of the flow regime continues to drain under unit gradient conditions, however the lower regime does not contribute to the drainage flux. The only unknown is the point in the profile where the two phenomena intersect.

A typical water content profile during stage two drainage using the two regime model is shown in Figure 4.2. Under actual field conditions, the rapid change in slope of the water content profile near the water table is unrealistic. However, this departure does not significantly affect the resulting flux calculations.

The intersection point of the two flow regimes can be calculated for a given time provided that the data are available for the soil water retention properties and hydraulic conductivity of the soil. This is done in the following steps:

1. Choose an initial drainage rate. By choosing a flux, the hydraulic conductivity is determined from Equation 4.7.

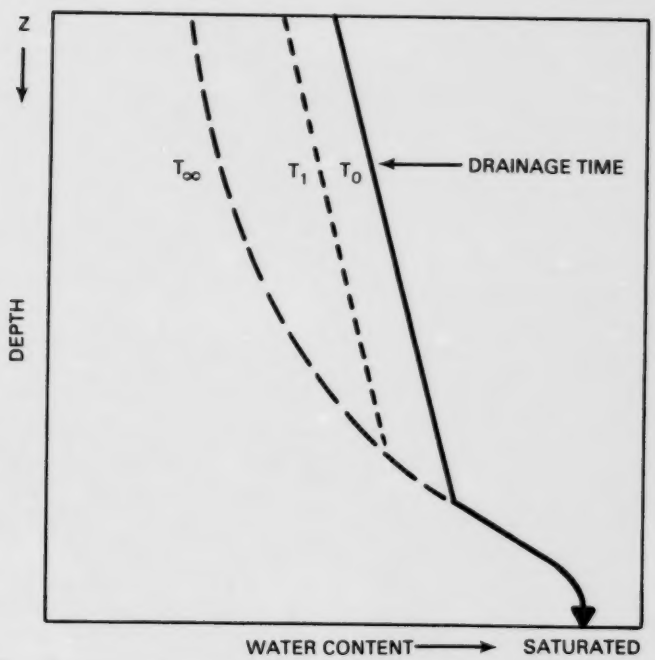


Figure 4.2. Moisture content profile during drainage to a shallow water table.

2. Solve Equations 4.2 and 4.8 for h and θ using soil water retention and hydraulic conductivity relationships for the soil of interest.

   The value of θ is the water content at the height, h, above a static water table. Effectively, the soil column has been shortened by the value of (Z - h). To calculate the time necessary to reach the flux chosen in step 1, Equation 4.6 must be modified to include the shortening effects:

$$t = \frac{Z_t - h}{\left.\frac{dK}{d\theta}\right|_{\theta = \theta_i}} \tag{4.9}$$

   where Z_t is the total depth of the column.

3. Solve Equation 4.9 for time necessary to reach the chosen flux.

4. Choose a new flux and repeat steps 1 through 3.

To test the validity of this new technique, an example landfill was modeled. The landfill was considered to contain a uniform waste material with hydraulic properties similar to the Yolo light clay data presented by Haverkamp et al. (1977). Pertinent soil data are as follows:

$$K_{SAT} = 1.0627 \text{ cm/day}$$
$$\theta_s = 0.495$$
$$\theta_r = 0.1797$$

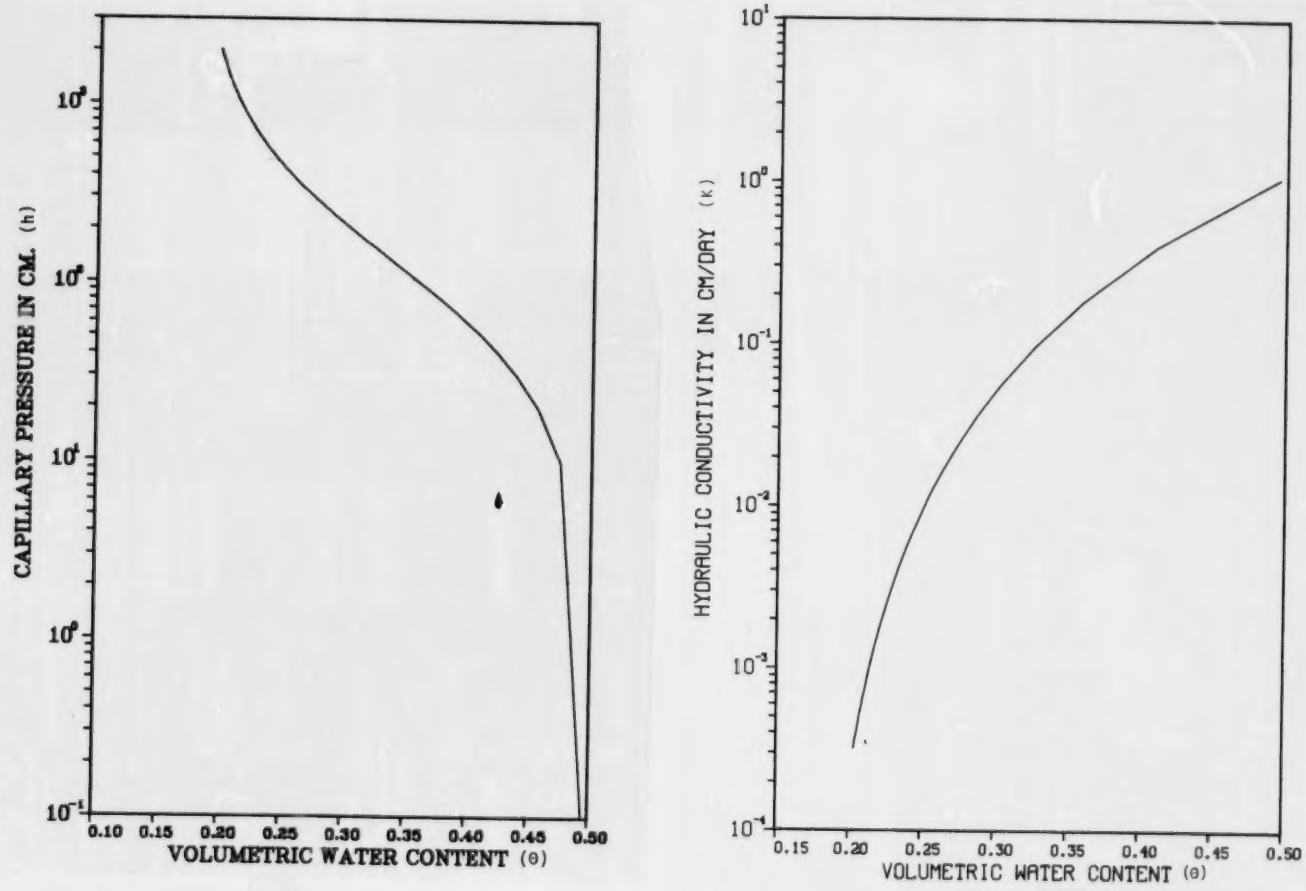
where K_{SAT} is the saturated conductivity, θ_s is the saturated water content, and θ_r is the residual water content.

The hydraulic properties (soil water retention and partially saturated hydraulic conductivity Equations 4.8 and 4.2, respectively) were calculated using the techniques of McKeon et al. (1983) and are shown in Figure 4.3. The functional forms of these curves are given below:

$$\theta(h) = (\theta_s - \theta_r)\left[\frac{\alpha}{\alpha + |h|^{\beta}}\right] + \theta_r \tag{4.10}$$

$$K(\theta) = K_{SAT}\left[\frac{\theta - \theta_r}{\theta_s - \theta_r}\right]^{\lambda} \tag{4.11}$$

where α, β, and λ are curve fitting parameters. Using curve-fitting techniques listed in McKeon et al. (1983) and the hydraulic properties listed above, values of 159.4, 1.03, and 3.14 were determined for α, β, and λ, respectively. Other equations are available for calculating hydraulic



a b

Figure 4.3. Properties of Yolo light clay.

conductivity from water retention curves. Criteria for selecting such equations are reviewed in McKeon et al. (1983).

The landfill is initially fully saturated and is taken to be 10 m thick. Underdrains are designed such that the final water table is located at the very bottom of the fill. The water content profile as a function of time is shown in Figure 4.4. As can be seen, a distinct break in slope occurs for each profile near the water table. This break occurs where the soil capillary pressure (pressure head) reaches equilibrium with the water table.

To assess the validity of this new method, it was compared with results from a fully implicit, one-dimensional, numerical ground-water flow code, UNSAT1D (Bond, Cole and Gutknecht 1982). The model was run using 50 equally spaced node points over the landfill. The water table was set at the bottom of the fill. Soil property curves given by Equations 4.10 and 4.11 were used as the input materials data for the model run.

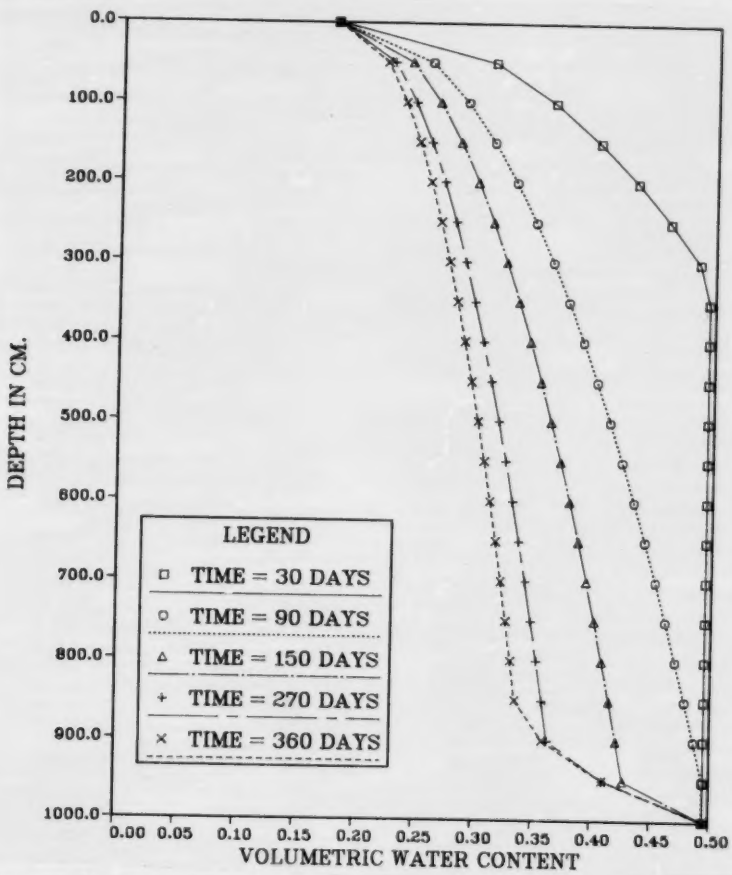


Figure 4.4. Water content profiles in Yolo light clay during drainage.

The resulting drainage out of the bottom of the column is shown in Figure 4.5. As can be seen, both solutions exhibit a period of constant drainage (stage one drainage) followed by a rapid decrease in drainage. At later times, the drainage from either solution decreases very slowly. The total change of fluid stored in the landfill at the end of 1 year (the length of time of numerical simulation) estimated by the analytical solution was 15% greater than that predicted by the numerical model. Although the analytical method overestimates the length of time required for stage one drainage, the solution closely matches the drainage characteristics at later times, with virtually identical drainage rates after 1 year for both the analytical and numerical solution.

Specific Yield Technique - Drum Sites

Many landfill cells may not contain primarily soil-like material. At the present time, many commercial waste sites dispose of primarily drummed, solidified waste. Leachate will be stored in the large voids between the drums as well as in the pore spaces of any backfilled soil. In most cases, the large voids will contain the most leachate. Under drainage conditions, these large voids will easily dewater leaving the leachate in the backfilled soil behind. The concept of free-draining pore spaces (voids) can be used to model fluid in drainage of drum disposal cells.

The specific yield of a porous media is defined as the volume of drainable pore space per unit volume of porous media. For landfills, specific yield is defined as the volume of leachate removed from a known volume of

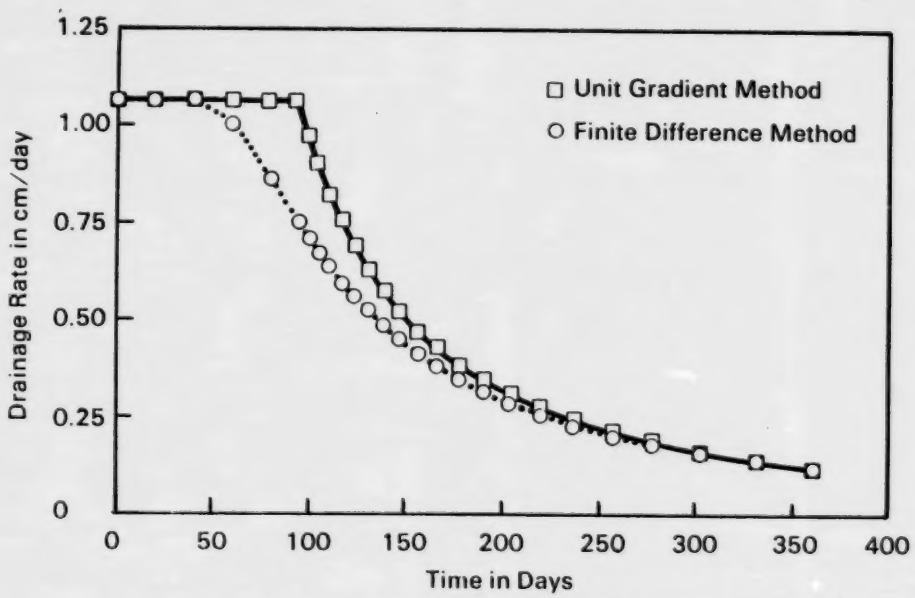


Figure 4.5. Comparison of drainage rates from Yolo light clay using unit gradient (analytical) analysis and finite difference (numerical) analysis.

landfill. This leachate volume is defined in several ways for this document: 1) as a measurement of the actual drainage, 2) as a value relating the leachate volume to the air space or void volume in a landfill, or 3) as the difference between water contents of soils at saturation and field capacity. Care is taken to define the volume from which leachate is draining for each specific yield application. In the case of a drum disposal cell, the drainable pore space consists primarily of the void spaces between the drums. The volume of these interdrum voids may be estimated using the number of drums in the cell, the amount of backfill soil and bulky waste, and the overall cell volume. Given an efficient underdrain system (one that will impede flow very little), leachate levels in the cell may be predicted using the specific yield approach.

Figure 4.6 shows aplan view of drum packing showing 5-cm spacing between the drums. Assuming there is no backfilled soil, the resulting interdrum void space shown in Figure 4.6 can be calculated as 33%.

Under draining conditions, the simple mass balance equation provides the basic tool necessary for the analysis:

$$\Delta\theta = q_i - q_{out} \tag{4.12}$$

Equation 4.12 states that the net flux of fluid out of the system is the rate of change of fluid storage in the system.

Using the assumption that the porous material has sufficient time to drain to equilibrium, the change in leachate level, ΔS, resulting from a drainage rate, q, is given by

$$\Delta S = \frac{q}{S_y} \tag{4.13}$$

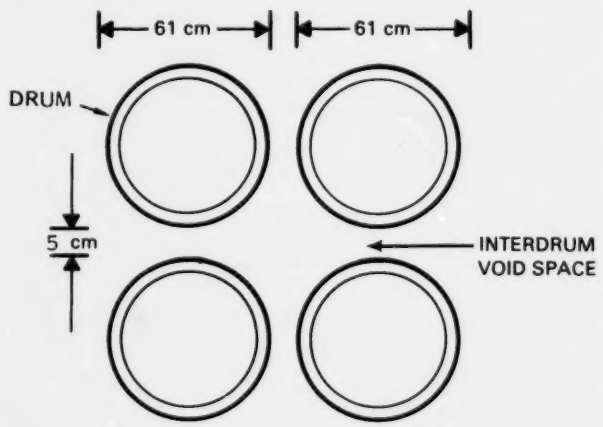


Figure 4.6. Plan view of typical drum packing.

where S_y is the specific yield, the difference between the saturated water content and the field capacity, and q is the rate of pumpage out of the bottom of the fill. Figure 4.7 shows the ranges of field values of specific yield for various geologic materials.

This method of analysis can also be applied to landfill cells where the leachate production is limited by the collection system. In these cases, the drainage rate, q, is fixed. In bulk waste landfills where this condition is met, the unit gradient method would not be applicable and the specific yield model should be applied.

SUMMARY OF MODELS

The models and example cases presented represent simplified conceptual models of hazardous waste landfills. Under actual field conditions, no one model may be completely applicable. The models chosen are designed for use under a variety of landfill configurations and waste types. Table 4.2 outlines the key points of the models and the typical data needed for their application.

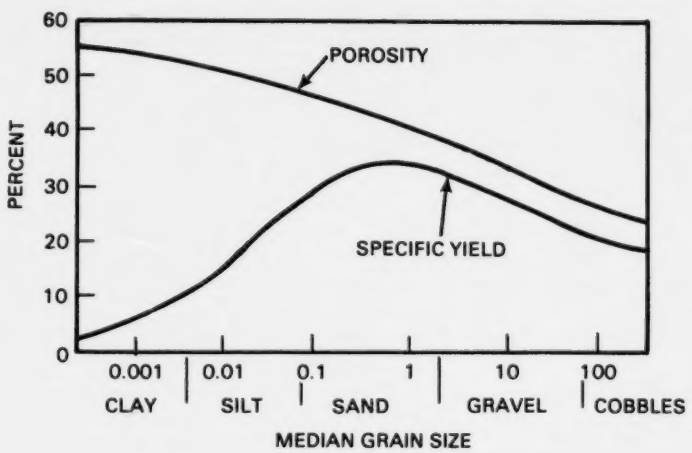


Figure 4.7. Ranges of specific yield for various geologic materials (Bear 1972).

TABLE 4.2. SUMMARY OF CONCEPTUAL MODELS

Model	Application	Resulting Data
Unit Gradient		
a) deep water table	Bulk waste forms, known hydraulic properties, uniform initial water content profile, deep landfill	Drainage flux versus time, water content profile versus time
b) shallow water table	Same as above except shallow landfill	Drainage flux versus time, water content profile versus time
Specific Yield	Unknown hydraulic properties, drummed or rapidly draining waste forms	Leachate level versus time

SECTION 5

ESTIMATION OF DRAINAGE RATES (LEACHATE FLUX) FROM CLOSED LANDFILLS

In this section, the models developed previously are incorporated into a methodology that may be used to estimate the leachate production from closed landfill cells. The methodology follows a decision tree approach in which field data on the characteristics of the landfill are used to move along the decision tree.

This section is divided into three subsections. In the first, the basic components/decisions of the decision tree methodology are described. In the second, guidelines for decision making and parameter estimation are discussed. Finally, four example cases are presented to demonstrate the use and applicability of the methodology.

MAJOR COMPONENTS OF THE METHODOLOGY

Figure 5.1 shows major components of the decision tree analysis. This analysis is designed to be applicable to a wide variety of closed landfill cells. The methodology begins with the basic question of what type of wastes are in the landfill. Based on discussions with operators and regulators, we found that most landfill cells are composed of 1) primarily bulky, soil-like waste (e.g., fly ash, contaminated soil, metal hydroxide sludges), 2) drummed or containerized waste with small amounts of backfilled soil, and 3) mixtures of bulky and drummed waste. All subsequent analysis in the methodology requires that this information be known.

The second major question is what level of leachate (saturated thickness) lies above the landfill liner. Although RCRA guidelines state that the level of leachate shall not exceed 30 cm above the liner, some landfills may not meet this requirement (Skinner 1981).

Once these questions have been answered, data must be assembled on the hydraulic properties of the waste. The properties needed for the analysis depend on the answers to the first two questions. The types and sources of data are discussed in detail later in this section.

After the landfill parameters have been identified, the user must decide whether the initial flow rates predicted by either model will exceed the capacity of the leachate collection and treatment system. This decision is based on a comparison of the saturated hydraulic conductivity of the waste to the designed leachate collection/treatment capacity. If the product of the conductivity and surface area of the landfill exceed the

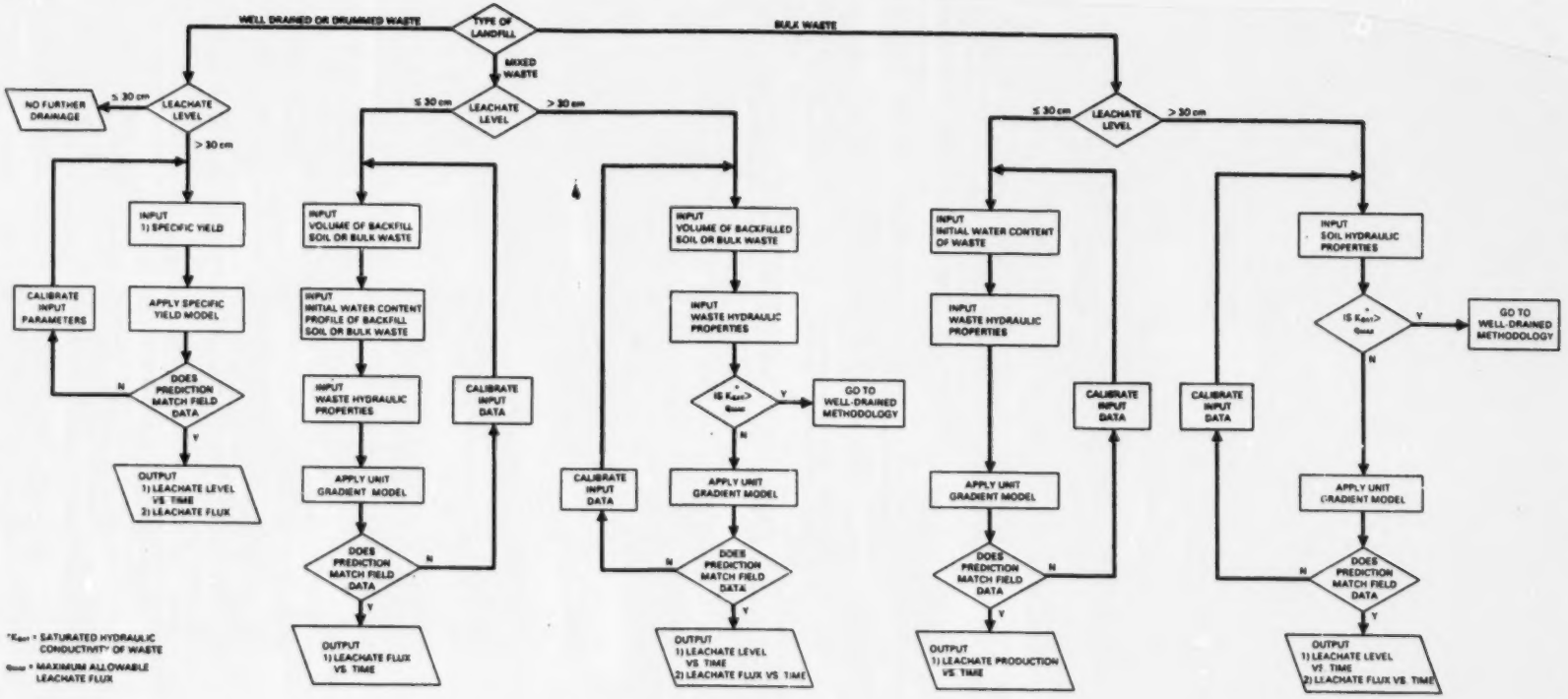

TYPE OF LANDFILL
WELL DRAINED OR DRUMMED WASTE
MIXED WASTE
BULK WASTE
LEACHATE LEVEL
≤ 30 cm
> 30 cm
NO FURTHER DRAINAGE
INPUT 1) SPECIFIC YIELD
APPLY SPECIFIC YIELD MODEL
CALIBRATE INPUT PARAMETERS
DOES PREDICTION MATCH FIELD DATA
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX
INPUT VOLUME OF BACKFILL SOIL OR BULK WASTE
INPUT INITIAL WATER CONTENT PROFILE OF BACKFILL SOIL OR BULK WASTE
INPUT WASTE HYDRAULIC PROPERTIES
APPLY UNIT GRADIENT MODEL
CALIBRATE INPUT DATA
OUTPUT 1) LEACHATE FLUX VS. TIME
INPUT VOLUME OF BACKFILLED SOIL OR BULK WASTE
IS Ksat > qmax
GO TO WELL-DRAINED METHODOLOGY
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX VS. TIME
INPUT INITIAL WATER CONTENT OF WASTE
OUTPUT 1) LEACHATE PRODUCTION VS. TIME
INPUT SOIL HYDRAULIC PROPERTIES
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX VS. TIME
*Ksat = SATURATED HYDRAULIC CONDUCTIVITY OF WASTE
qmax = MAXIMUM ALLOWABLE LEACHATE FLUX

Figure 5.1. Decision tree analysis to determine leachate production from closed landfills.

capacity of the system, then the leachate production rate will be controlled by the system capacity. If this product is less than the designed capacity, the production rate will be controlled by the hydraulic properties of the waste.

At this point in the decision tree, the proper model is applied to the site data, and leachate production is predicted. If field data on the leachate production are available, these are compared to the predicted results and the model may be calibrated for better long-term utility.

GUIDELINES FOR DECISION MAKING AND PARAMETER ESTIMATION

Each of the decision blocks shown in Figure 5.1 requires considerable input data from the user. In some cases, these data may be quite simple to obtain (i.e., measurement of the leachate level in monitoring wells or standpipes). Others, however, such as estimating the hydraulic parameters of bulk wastes may require more data than are available to the user. This section provides the user with some guidelines for data gathering, interpreting, and parameter estimation techniques. These guidelines are presented in the order in which they appear in the decision tree shown in Figure 5.1.

Type of Waste in the Landfill

The two modeling techniques presented in Section 4 are designed for use on two different types of wastes. The unit gradient technique was developed for use at landfills composed of soil-like materials in which fluid flows through the pore spaces obeying Darcy's Law. The second technique (specific yield) is designed for use in drummed disposal sites where fluid flow is controlled by the large void spaces between the drums. In this type of landfill, leachate moves freely to the leachate collection system, and little energy is expended in passing through the waste. Difficulties arise, however, at those sites that contain mixtures of bulk and drummed waste. It is suggested that the user choose the mixed-waste option if the volume of bulk waste exceeds 25% of the total waste volume. This is an arbitrary cutoff point and will require more field data to validate.

Leachate Level

If the landfill is operated in accordance with present RCRA regulations, no more than 30 cm of leachate will be standing above the liner or underdrain system.

To proceed with the methodology, the user must estimate the leachate level. Direct measurement of leachate levels may be made in leachate standpipes or by closing lateral leachate collection lines and monitoring the hydrostatic pressure. Existing field data (Skinner 1981) have shown that leachate levels in landfills require significant time to reach equilibrium after pumping; therefore, all leachate level measurements should be taken before any pumping.

Estimation of Profile Water Content

If a bulk or mixed-waste landfill has been operated in accordance with the RCRA guidelines, the user must determine the water content of the waste at the time of closure. Moisture monitoring equipment installed in the waste or core samples of the waste taken at the time of closure may be used to estimate the water content of the waste.

Estimation of Waste Hydraulic Properties

The decision tree analysis in Figure 5.1, requires the user to input data on the hydraulic properties of the waste material in the landfill. Table 4.1 summarizes the hydraulic property data found in the literature. The table shows that few data are available at this time.

The first input needed is the saturated hydraulic conductivity of the waste. In bulk waste sites, disturbed or undisturbed core samples may be analyzed in the laboratory for saturated hydraulic conductivity. Methods for determining saturated hydraulic conductivity are reviewed in Black (1965). In drummed or freely draining sites, the saturated hydraulic conductivity is not needed for the calculations. In mixed-waste landfills, the user must decide which of the waste forms controls the drainage of leachate to the collection systems. At sites where little bulk material or backfill soil has been used, the voids between the drums will control the fluid migration. In sites where drummed waste is a small portion of the disposal volume and bulk waste has been placed to minimize large void spaces, the fluid drainage will be controlled by the backfill soil. In this case, saturated conductivity measurements must be made or estimated for the bulk waste and soil. Section 6 discusses the effects of void spaces in more detail.

For bulk waste sites, data on the relationship of hydraulic conductivity versus water content and the water content versus capillary pressure head are required. Although these data may be obtained from field tests (Wilson 1982), most often they are determined in the laboratory from core samples. Detailed descriptions of the various laboratory techniques are reviewed in Black (1965). If laboratory data are not available on the waste, the user may substitute data from equivalent soils based on particle-size analysis. These data will provide a crude estimate of the properties.

For drummed waste sites, the specific yield of the waste must be estimated. The specific yield is a measure of the volume of drainable liquid per unit volume of landfill cell. For sites containing only drummed wastes, the drainable volume is given by the soil and void space around the drums. This value may be calculated by subtracting the total drum volume (number of drums • volume of one drum) from the total volume of the landfill cell. In most drum disposal landfills, however, a cover is placed on top of each lift of drums at the end of the day. Assuming that this daily cover does not restrict fluid drainage significantly, and itself does not contain significant volumes of leachate, then the interdrum volume may be calculated by subtracting the total drum volume and the backfill soil volume from the

total landfill volume. The specific yield of the landfill is then calculated by dividing the interdrum void volume by the total landfill volume.

$$S_y = \frac{\text{interdrum void volume}}{\text{total volume of landfill}} = \frac{Q}{LFV} \qquad (5.1)$$

If the backfill soil is believed to contribute leachate, the above calculation may be modified. This modification consists of volume-weighting the specific yield. To do this, the user first estimates the interdrum specific yield as above. Next, the user determines the backfill specific yield, either through laboratory analysis or from Figure 4.7. The overall landfill specific yield is then calculated on a volume basis:

$$S_{yt} = Sy + X_{BF} \cdot Sy_{BF} \qquad (5.2)$$

where X_{BF} is the ratio of backfill soil volume to the total landfill volume and Sy and Sy_{BF} are the specific yields of the interdrum voids and backfill soil, respectively. This modification is based on the assumption that the saturated conductivity of the backfill soil does not limit drainage from the interdrum voids.

For mixed-waste cells, the hydraulic parameters needed are based on the user's decision as to which waste form controls the drainage process. In mixed cells where the bulk wastes are believed to be free draining, the volume-weighted specific yield must be calculated. At sites where the bulk waste and backfill soil are low in conductivity or interdrum void space has been minimized by efficient drum packing, the relationships of conductivity to water content and capillary pressure to water content of the soil will need to be determined.

EXAMPLE CASES

In this section, four example cases are given to illustrate the methodology developed for estimation of leachate production from closed landfills. In each case, a step-by-step analysis is given showing the assumptions and calculations necessary.

Each example case is designed to illustrate the applicability of the methodology to various forms of waste disposal landfills. In the first case, the landfill is a bulk waste site filled with leachate and illustrates the use of the unit gradient technique. The second and third examples show the use of the specific yield technique by modeling landfills where 1) backfill soil is an unimportant source of stored water and 2) the backfill soil affects the length of time needed to drain the site. In the fourth example, a landfill is modeled in which the leachate level has been kept in accordance with the RCRA regulations. In this last case, it is shown that small amounts of leachate will be produced from bulk waste landfills for many years after the site is closed.

In each of the example cases, it is assumed that no precipitation infiltrates through the cover. Under actual field conditions, covers cannot be expected to be perfectly impermeable and some water may move through the cover and into the waste. For a properly installed cover, this amount of fluid influx will be insignificant compared with early stages of drainage. Over the long term, the landfill will reach a steady-state condition in which the leachate production will equal the influx through the cover. For the examples presented, the leachate production rates may be adjusted for this cover influx by adding the cover influx rate to the predicted rate. In addition, each of the example cases assumes that no fluid passes through the sidewalls or liner of the landfill.

Example Case 1

In this example, the landfill is a rectangular bulk waste disposal cell, 1 ha in surface area and 10 m deep. The leachate level at the time of closure is also 10 m. The waste material hydraulic properties are similar to Yolo light clay (Figures 4.3a and 4.3b). The leachate collection system can accept a maximum of 100 m^3/day.

Figure 5.2 shows the pathway taken in the analysis. The numbers in Figure 5.2. refer to the steps that must be taken to solve example case 1.

1. The waste material in the cell is a bulk waste.

2. The leachate level is measured to be 10 m.

3. The waste hydraulic properties have been determined in the laboratory (Haverkamp et al. 1977). Equations 4.10 and 4.11 are used with the hydraulic properties and curve-fitting parameters for Yolo light clay that were given on page 20.

$$\theta(h) = (0.495 - 0.1797)\left[\frac{159.4}{159.4 + (h)^{1.03}}\right] + 0.1797 \qquad (5.3)$$

$$K(\theta) = (1.0627) \cdot \left[\frac{\theta - 0.1797}{0.495 - 0.1797}\right]^{3.14} \qquad (5.4)$$

where θ is the volumetric water content, h is the capillary pressure head (cm) and K is the partially saturated hydraulic conductivity (cm/day).

4. The maximum flux from the waste is calculated as the product of the saturated hydraulic conductivity multiplied by the surface area of the landfill cell (1 ha = 10^4 m^2)

$$Q_{max} = K_{SAT} \cdot A \qquad (5.5)$$

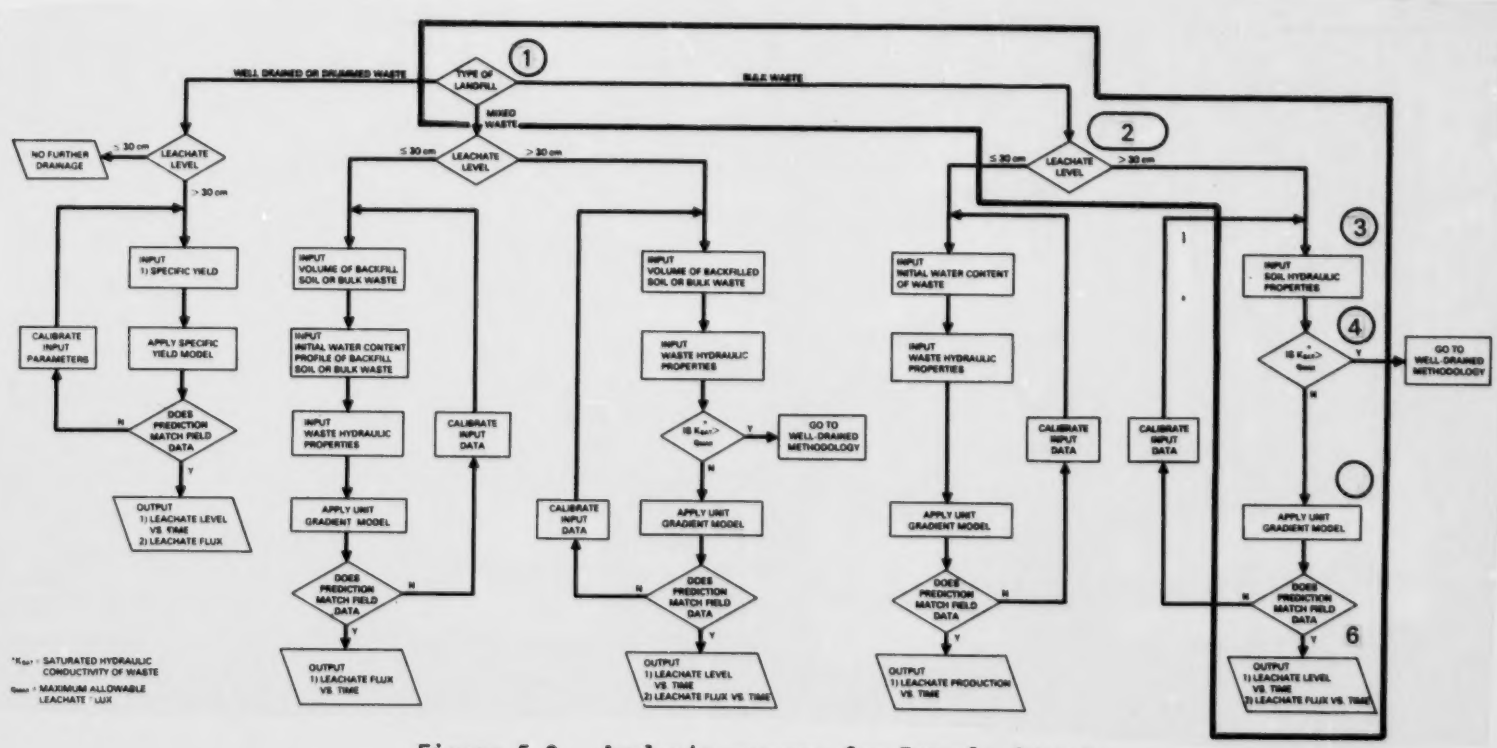

WELL DRAINED OR DRUMMED WASTE
TYPE OF LANDFILL
1
BALE WASTE
MIXED WASTE
2
NO FURTHER DRAINAGE
≤ 30 cm
LEACHATE LEVEL
> 30 cm
INPUT 1) SPECIFIC YIELD
APPLY SPECIFIC YIELD MODEL
CALIBRATE INPUT PARAMETERS
DOES PREDICTION MATCH FIELD DATA
N
Y
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX
INPUT VOLUME OF BACKFILL SOIL OR BULK WASTE
INPUT INITIAL WATER CONTENT PROFILE OF BACKFILL SOIL OR BULK WASTE
INPUT WASTE HYDRAULIC PROPERTIES
APPLY UNIT GRADIENT MODEL
CALIBRATE INPUT DATA
OUTPUT 1) LEACHATE FLUX VS. TIME
IS K_{sat} > Q_{max}
GO TO WELL DRAINED METHODOLOGY
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX VS. TIME
INPUT INITIAL WATER CONTENT OF WASTE
OUTPUT 1) LEACHATE PRODUCTION VS. TIME
3
INPUT SOIL HYDRAULIC PROPERTIES
4
6
K_{sat} = SATURATED HYDRAULIC CONDUCTIVITY OF WASTE
Q_{max} = MAXIMUM ALLOWABLE LEACHATE FLUX

Figure 5.2. Analysis process for Example Case 1.

$$Q_{max} = 1.0627 \times 10^{-2} \text{ m/day} \cdot 10^4 \text{ m}^2 = 1.0627 \times 10^2 \text{ m}^3\text{/day}$$

Therefore, the cell drainage rate will be controlled by the waste since the capacity of the leachate collection system is 200 m^3/day.

5. Apply the unit gradient model to determine stage one drainage time.

Equation 4.6 relates the time of stage one drainage (during this time, the leachate flux is equal to the saturated hydraulic conductivity) as

$$t_{S1} = \frac{Z_t}{\left.\frac{dK}{d\theta}\right|_{\theta = \theta_{SAT}}} \tag{5.6}$$

where t_{S1} is the time in days of stage one drainage, $\left.\frac{dK}{d\theta}\right|_{\theta = \theta_{SAT}}$ is the slope of the conductivity/water content curve (Figure 4.3b) at the saturated water content and Z is the initial saturated thickness of the landfill (10 m) from the data presented in step 2.

The derivative of Equation 5.4 is calculated as

$$\left.\frac{dK}{d\theta}\right|_{\theta = 0.495} = \frac{3.14 \cdot 1.0627}{(0.495 - 0.1797)} \cdot \left[\frac{0.495 - 0.1797}{0.495 - 0.1797}\right]^{(3.14 - 1.0)}$$

$$= 10.58 \text{ cm/day} = 10.58 \times 10^{-2} \text{ m/day}$$

The time of stage one drainage, t_{S1} may then be calculated as

$$t_{S1} = \frac{10 \text{ m}}{10.58 \times 10^{-2} \text{ m/day}} = 95 \text{ days}$$

6. Calculate stage two fluxes and times. Using the steps outlined in Section 4, the times to reach the prescribed fluxes may be calculated. Calculations for each step are shown below as an example:

6a. A flux, q, of nine-tenths of the saturated conductivity is chosen ($q = 0.9 \cdot K_{SAT} = 9 \times 10^{-1}$ cm/day)

6b. The water content, θ, corresponding to this flux is calculated from Equation 5.4 or can be taken from Figure 4.36.

$$K = 9 \times 10^{-1} = 1.0627\left[\frac{\theta - 0.1797}{0.495 - 0.1797}\right]^{3.14}$$

$$\theta = 0.478 \ (cm^3/cm^3)$$

6c. The capillary pressure, h, corresponding to this water content may be calculated from Equation 5.3 or can be taken from Figure 4.3a.

$$\theta = 0.478 = (0.495 - 0.1797)\left[\frac{159.4}{159.4 + (h)^{1.03}}\right] + 0.1797$$

$$h = 8.5 \text{ cm} = 0.08 \text{ m.}$$

6d. Equation 4.9 allows the user to solve for the time necessary to reach the flux chosen above

$$t = \frac{Z_t - h}{\left.\frac{dK}{d\theta}\right|_{\theta = 0.478}}$$

6e. Evaluating $\frac{dK}{d\theta}$ at $\theta = 0.478$ yields

$$\left.\frac{dK}{d\theta}\right|_{\theta = 0.478} = \frac{(3.14)(1.0627)}{0.495 - 0.1797}\left[\frac{0.478 - 0.1797}{0.495 - 0.1797}\right]^{(3.14 - 1)}$$

$$\left.\frac{dK}{d\theta}\right|_{\theta = 0.478} = 9.39 \text{ cm/day} = 9.4 \times 10^{-2} \text{ m/day}$$

6f. The time to reach a flux of 9×10^{-1} cm/day can now be calculated from Equation 4.9

$$t = \frac{Z_t - h}{\left.\frac{dk}{d\theta}\right|_{\theta = 0.478}} = \frac{10 - 0.08}{9.4 \times 10^{-2}}$$

or t = 106 days

The calculations are repeated by choosing a different flux and repeating the steps. In most cases, fluxes such as 0.9 • K_{SAT}, 0.5 • K_{SAT}, 0.1 • K_{SAT}, 0.01 • K_{SAT}, and 0.005 • K_{SAT} will define the predicted leachate production curve. To calculate the total daily flow for the entire landfill, the flux, q, is multiplied by the surface area of the landfill, which is a variation of Equation 5.5.

$$Q_{TOTAL} = q \cdot A$$

The resulting daily flux, Q_{TOTAL} versus time for the example problem is shown in Figure 5.3. This figure indicates that the leachate production will be constant during stage one drainage, but will rapidly decrease to a small and nearly constant rate after 300 days.

Example Case 2

In this example problem the landfill is a rectangular drummed waste disposal cell , 1 ha in surface area, and 10 m deep. Backfill soil has been placed in 10 cm layers between each lift of drums and the operating records indicate that little attempt was made to place soil between the drums. The estimated drum packing density is shown in Figure 4.6. At the time of closure, the leachate level was 10 m above the leachate collection system. The leachate collection system can accept a maximum of 100 m^3/day.

Figure 5.4 shows the pathway taken in the analysis.

1. The waste material in the cell is primarily drummed.
2. The leachate level has been measured to be 10 m.
3. The waste specific yield is estimated as in Equation 5.1, which assumes that backfill material does not contribute to or restrict drainage.

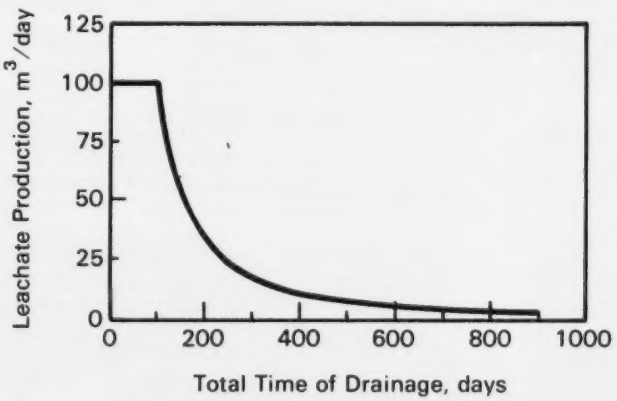


Figure 5.3. Leachate production for Example Case 1.

First, the number of drums in the cell must be estimated. This estimate can either be made from operating records or by calculating the number of drums based on the packing density. For this example, it is assumed that the packing density is similar to Figure 4.6 and the distance between drums is 5 cm. The number of drums in one lift of the 1 ha landfill is given by

$$\text{number of drums/lift} = \frac{\text{total area}}{\text{area of one drum}} \tag{5.7}$$

$$= \frac{10{,}000\ m^2}{(.61\ m + .05\ m)^2} = 22{,}957 \text{ drums}$$

The number of lifts in the cell is calculated by

$$\text{number of lifts} = \frac{\text{total thickness of landfill}}{\text{drum height + daily cover height}} \tag{5.8}$$

$$= \frac{10\ m}{.90\ m + .10\ m} = 10 \text{ lifts}$$

The total number of drums is calculated by

$$\text{number of drums} = \text{number of drums/lift} \cdot \text{number of lifts} \tag{5.9}$$
$$= 229{,}570 \text{ drums}$$

The total volume of drums is given by

$$\text{Total drum volume} = \text{number of drums} \cdot \text{volume of one drum} \tag{5.10}$$

A typical 55-gal drum has a volume of 0.2079 m^3 (1 gal = 0.00378 m^3). The total drum volume in the landfill is 47,728 m^3.

The volume of daily cover soil in the cell may be estimated by

$$\text{Volume of cover soil} = \text{number of lifts} \cdot \text{cover soil thickness} \cdot \text{landfill area} \tag{5.11}$$
$$= 10 \times 0.10\ m \cdot 10{,}000\ m$$
$$= 10{,}000\ m^3$$

The total volume of the landfill is given by

$$\text{Total landfill volume} = \text{landfill area} \cdot \text{landfill depth} \tag{5.12}$$
$$= 10{,}000\ m^2 \cdot 10\ m$$
$$= 100{,}000\ m^3$$

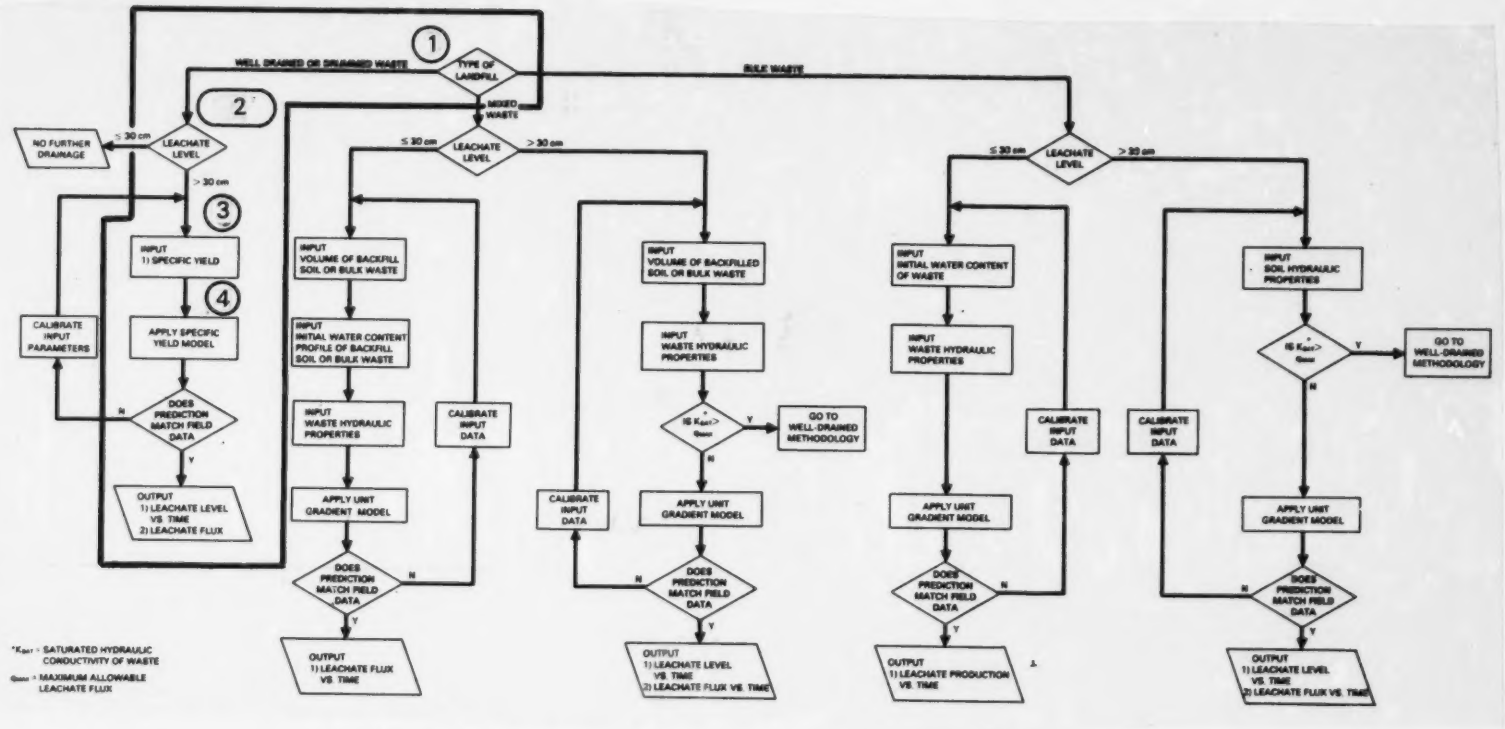


Figure 5.4. Analysis process for Example Case 2.

Therefore, the volume of the landfill filled with large voids is

$$\text{Void volume} = \text{total landfill volume} - \text{drum volume} - \text{soil volume} \quad (5.13)$$
$$= 100{,}000 - 47{,}728 - 10{,}000$$
$$= 42{,}272\ m^3$$

In the specific yield model, all of the fluid contained in the void space is assumed to drain. The specific yield per Equation 5.1 is therefore

$$Sy = \frac{\text{Interdrum void volume}}{\text{Total volume of landfill}} \quad (5.14)$$

$$Sy = \frac{42{,}272\ m^3}{100{,}000\ m^3} \approx 0.42$$

4. Apply the specific yield model.

Equation 4.13 requires that the designed flux rate and the waste specific yield be known to calculate the rate of fall of the leachate level. The total flux, Q, by design is 100 m^3/day; therefore, the leachate collection system controls the drainage rate from the landfill. The drainage rate, q, is obtained by dividing the total flux, Q, by the landfill Area, A:

$$q = \frac{Q}{A} = \frac{100\ m^3/day}{10{,}000\ m^2} = 0.01\ m/day \quad (5.15)$$

The rate of lowering of the leachate level is given by

$$\Delta S = \frac{q}{S_y} \quad (5.16)$$

$$\Delta S = \frac{0.01\ m/day}{0.42\ \ m^3/m^3} = 0.024\ m/day$$

The time required to completely dewater the landfill is given by

$$\text{Time to dewater} = \frac{\text{initial saturated thickness}}{\Delta S} \quad (5.17)$$

$$= \frac{10\ m}{0.024\ m/day} = 416\ days$$

The predicted leachate level and leachate production rate are shown in Figure 5.5. As can be seen, the leachate production is constant, reflecting the specified design capacity while the leachate level falls at a constant rate of 0.024 m/day.

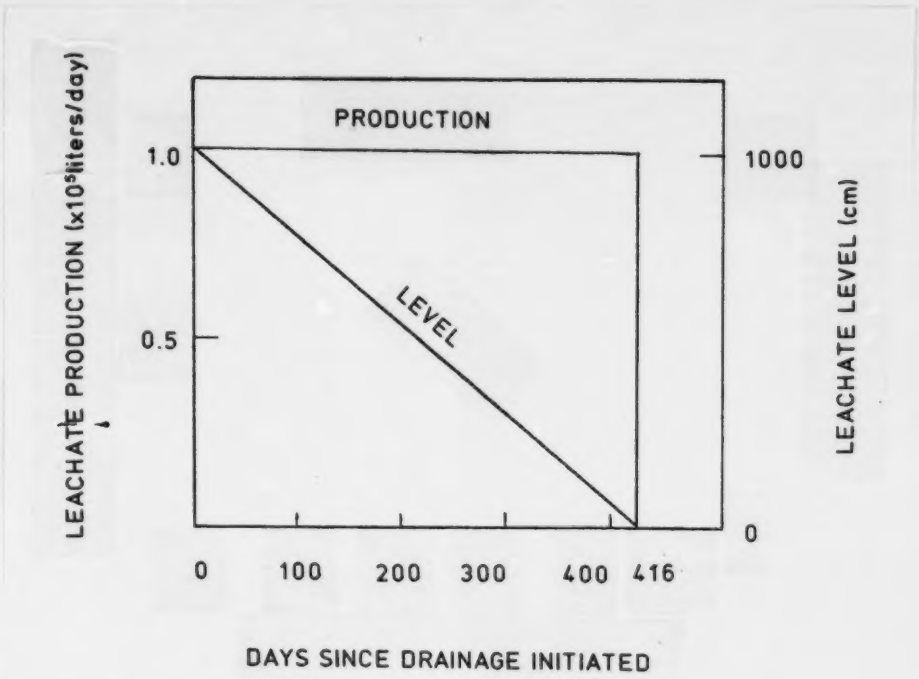


Figure 5.5. Predicted leachate production and level for Example Case 2

Example Case 3

In this case, the landfill cell is filled with a mixture of backfill soil and drummed waste. The composition of the cell is similar to that of Example 2; however, it is assumed that more backfill soil has been used and approximately 25% of the interdrum voids have been filled with backfill soil. The landfill has the same dimensions as Example 2 and contains 10 m of leachate above the liner. The leachate collection system is designed for a 100 m^3/day capacity. Figure 5.6 shows the analysis process.

1. The landfill is classified as a mixed-waste landfill.

2. The leachate level is 10 m.

3. The volume of cover soil is 10,000 m^3 (Equation 5.11) and an additional 25% of the landfill void volume (0.25 · 42,272) = 10,568 m^3 also contains backfill soil. The volume of interdrum void space is, therefore, 0.75 · 42,272 = 31,704 m^3.

In this case, as in Example 2, the leachate collection system controls the drainage rate and the specific yield approach may be taken. Equation 5.2 is used to estimate the specific yield accounting for drainage from the backfill soil.

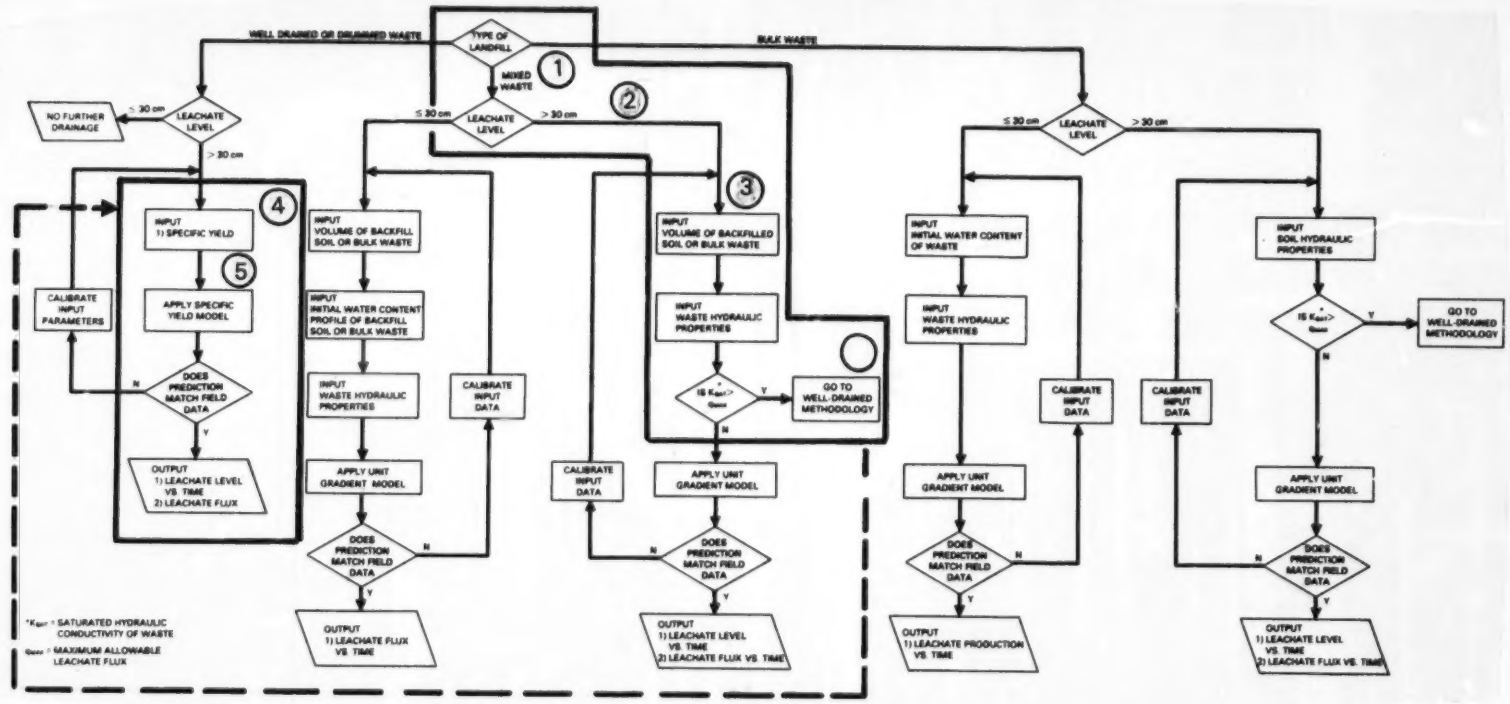

WELL DRAINED OR DRUMMED WASTE
TYPE OF LANDFILL
MIXED WASTE
BULK WASTE
1
2
3
4
5
LEACHATE LEVEL
≤ 30 cm
> 30 cm
NO FURTHER DRAINAGE
INPUT 1) SPECIFIC YIELD
APPLY SPECIFIC YIELD MODEL
DOES PREDICTION MATCH FIELD DATA
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX
CALIBRATE INPUT PARAMETERS
INPUT VOLUME OF BACKFILL SOIL OR BULK WASTE
INPUT INITIAL WATER CONTENT PROFILE OF BACKFILL SOIL OR BULK WASTE
INPUT WASTE HYDRAULIC PROPERTIES
APPLY UNIT GRADIENT MODEL
OUTPUT 1) LEACHATE FLUX VS. TIME
CALIBRATE INPUT DATA
INPUT VOLUME OF BACKFILLED SOIL OR BULK WASTE
INPUT WASTE HYDRAULIC PROPERTIES
IS K*sat > qmax
GO TO WELL-DRAINED METHODOLOGY
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX VS. TIME
INPUT INITIAL WATER CONTENT OF WASTE
OUTPUT 1) LEACHATE PRODUCTION VS. TIME
INPUT SOIL HYDRAULIC PROPERTIES
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX VS. TIME
*Ksat = SATURATED HYDRAULIC CONDUCTIVITY OF WASTE
qmax = MAXIMUM ALLOWABLE LEACHATE FLUX

Figure 5.6. Analysis process for Example Case 3.

4. To estimate the specific yields of the drums and soil individually, two specific yields are needed. The drum specific yield can be estimated similarly to that in Example 2, noting that the void space has been reduced by 25%. The specific yield of drums is given by

$$Sy = \frac{\text{interdrum void vol.}}{\text{total vol. of landfill - backfill soil vol.}} = \frac{(0.75)(42,272)}{100,000 - 20,568} = 0.40 \quad (5.18)$$

The specific yield of the backfill soil can be measured experimentally or estimated from Figure 4.7. For this analysis, the specific yield of the backfill soil is taken to be 25%.

The effective specific yield Sy (Equation 5.2) of the landfill is given by

$$Sy_T = Sy + X_{BF} \cdot S_{BF} \quad (5.19)$$

$$= \frac{31,704 m^3}{100,000 m^3} \cdot 0.40 + \frac{20,568 m^3}{100,000 m^3} \cdot 0.25$$

$$= 0.45 = 45\%$$

5. Apply the specific yield model.

As in Example 2, Equations 5.16 and 5.17 may be used to estimate the rate of fall of the leachate level in the landfill.

$$\Delta S = \frac{\frac{100 m^3/day}{10,000 m_2}}{0.45} = 0.022 \text{ m/day} \quad (5.20)$$

The time required to completely drain the landfill is given by

$$\text{Time to dewater} = \frac{\text{initial saturated thickness}}{\Delta S} \quad (5.21)$$

$$t = \frac{10 m}{0.022 m/day} = 454 \text{ days}$$

Figure 5.7 shows the predicted leachate production and leachate level for Example Case 3. As in Example Case 2, the leachate production is constant while the leachate level falls at a constant rate of 0.022 m/day.

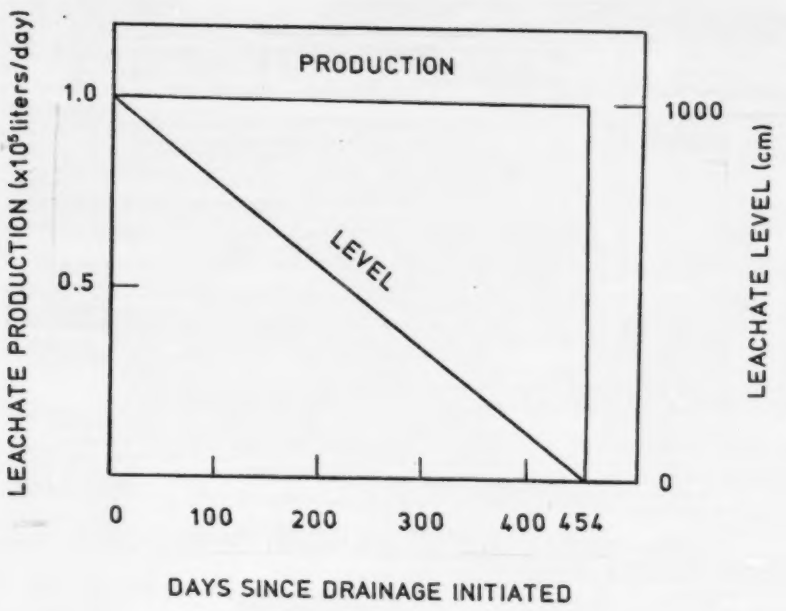


Figure 5.7. Predicted leachate production and level for Example Case 3.

Example Case 4

In this case, the landfill cell is 1 ha in area and contains a mixture of contaminated soil similar to Yolo light clay and drums. At the time of closure, the leachate level is at 30 cm above the leachate collection system in compliance with the RCRA guidelines. Figure 5.8 shows the pathway taken for this example

1. The cell is a mixed-waste cell. For this analysis, it is assumed that 50% of the total landfill volume is filled with soil, 40% of the cell contains drummed waste, and the remaining 10% are large air-filled voids. It is assumed that the soil is continuous and the drums do not reduce the conductivity of the soil.

2. The leachate level is at 30 cm.

3. The ratios of wastes are as given above.

4. The initial water content of the contaminated soil is taken to be 25%. This figure represents the field capacity of Yolo light clay in Figure 4.3a.

5. The contaminated soil is similar to the Yolo light clay soil discussed in Section 4. The front part of this section discusses how to determine this information.

6. Calculate stage one drainage.

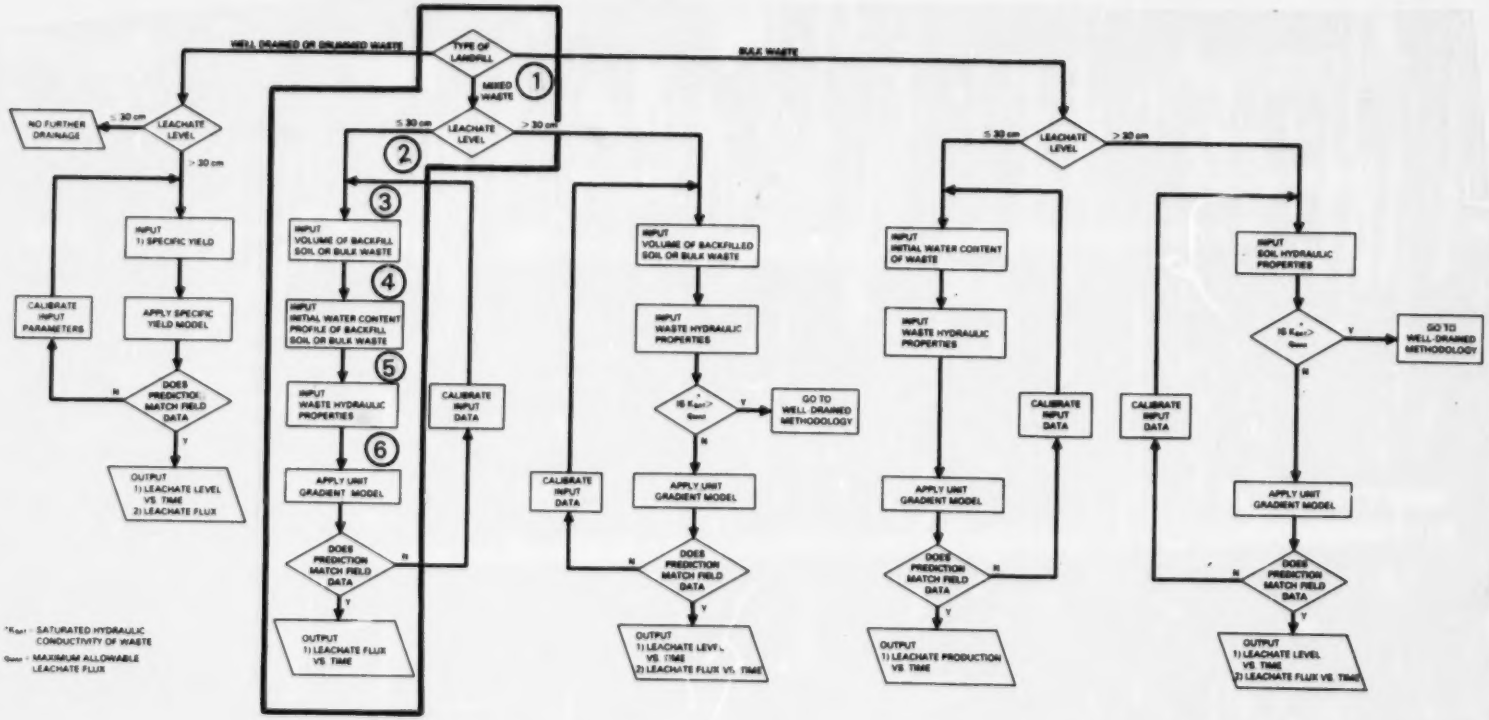

TYPE OF LANDFILL
WELL DRAINED OR DRAINED WASTE
MIXED WASTE
BULK WASTE
LEACHATE LEVEL
≤ 30 cm
> 30 cm
NO FURTHER DRAINAGE
INPUT 1) SPECIFIC YIELD
APPLY SPECIFIC YIELD MODEL
CALIBRATE INPUT PARAMETERS
DOES PREDICTION MATCH FIELD DATA
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX
INPUT VOLUME OF BACKFILL SOIL OR BULK WASTE
INPUT INITIAL WATER CONTENT PROFILE OF BACKFILL SOIL OR BULK WASTE
INPUT WASTE HYDRAULIC PROPERTIES
APPLY UNIT GRADIENT MODEL
OUTPUT 1) LEACHATE FLUX VS. TIME
CALIBRATE INPUT DATA
INPUT WASTE HYDRAULIC PROPERTIES
IS Ksat> Qmax
GO TO WELL DRAINED METHODOLOGY
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX VS. TIME
INPUT INITIAL WATER CONTENT OF WASTE
OUTPUT 1) LEACHATE PRODUCTION VS. TIME
INPUT SOIL HYDRAULIC PROPERTIES
GO TO WELL-DRAINED METHODOLOGY
OUTPUT 1) LEACHATE LEVEL VS. TIME 2) LEACHATE FLUX VS. TIME
*Ksat - SATURATED HYDRAULIC CONDUCTIVITY OF WASTE
Qmax - MAXIMUM ALLOWABLE LEACHATE FLUX

Figure 5.8. Analysis process for Example Case 4.

Because the waste is not fully saturated, the stage one drainage calculation must account for the presence of the static water table conditions. Figure 5.9 shows the idealized water content profile at the time of closure. As can be seen, the volumetric water content is constant the first 5 m, but increases to saturation at the leachate collection level. Equation 4.9 may be applied to account for the water table condition.

The time for stage one drainage to be completed is given.

$$t_{S1} = \frac{Z - h}{\left.\frac{dK}{d\theta}\right|_{\theta = \theta_i}} \tag{5.22}$$

where Z is the total depth of the landfill, and h is the capillary pressure at the water content, θ_i, in the top 5 m.

Since θ_i is known (0.25 for the landfill), h may be determined from Figure 4.3a or calculated from the relationship of capillary pressure to water content given by Equation 4.10.

$$\theta_i = (\theta_s - \theta_r)\left(\frac{\alpha}{\alpha + |h|^{\beta}}\right) + \theta_r$$

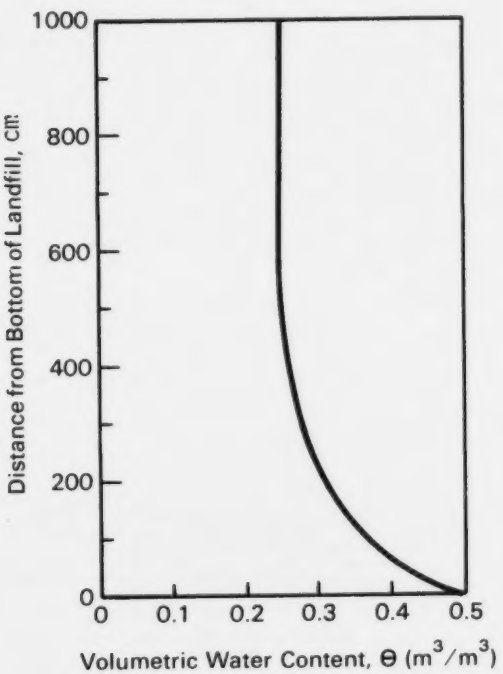


Figure 5.9. Idealized water content profile at time of closure for Example Case 4.

Using Figure 4.3a for the parameters for Yolo light clay, h is 5m.

The term $\left.\frac{dK}{d\theta}\right|_{\theta = \theta_i}$ is calculated as in Example Case 1 (Equation 5.6) except that θ_i is now taken as 0.25.

The time for stage one drainage to occur is given by

$$t_{S1} = \frac{10.0_m - 5.0_m}{0.40 \times 10^{-2}\ m/day} = 1250.0 \text{ days}$$

The leachate flux, q, during stage one may be calculated from the relationship of the hydraulic conductivity to volumetric water content (Equation 4.11) or from Figure 4.3b:

$$q = K(\theta) = K_{SAT} \frac{\theta_i - \theta_r}{\theta_s - \theta_r}^{\lambda} \qquad (5.23)$$

or

$$q = (1.0627) \left[\frac{0.25 - 0.1797}{0.495 - 0.1797}\right]^{3.14}$$

$$q = 9.5 \times 10^{-3}\ cm/day$$

The total leachate flux, Q, to the drainage system in this case is not obtained as in Example Case 2 because the soil does not comprise the entire area of the landfill. Because only 50% of the cell contains soil, the total leachate flux, Q, is given by

$$Q = q \times \frac{\text{volume of soil}}{\text{volume of landfill}}$$

$$= (9.5 \times 10^{-5} m/day)(.5)$$

$$Q = 4.7 \times 10^{-5}\ m^3/day$$

At this point, stage two drainage may be calculated in the same manner as Example 1. However, at such a small rate of total flux, leachate production during stage one drainage would be considered insignificant. Only limited pumping of the leachate would be necessary to maintain the level at 30 cm above the liner.

SECTION 6

APPLICATION OF SPECIFIC YIELD TO LEACHATE PRODUCTION

The majority of hazardous waste sites containing bulk wastes have been poorly characterized and little is known about the physical attributes of the waste materials. Numerical and analytical modeling of drainage requires estimates of the water retention and hydraulic conductivity curves for the waste, which are seldom available. Therefore, application of the conceptual models discussed in Section 4 is limited to specific yield for prediction of leachate production at these waste sites. Three field applications of the specific yield approach are examined in this section. These applications address 1) an estimate of the specific yield from leachate level records taken at a commercially operated waste site, 2) a study of the leachate level behavior of a closed hazardous waste site, and 3) an evaluation of the effect of common variables in waste site construction such as barrel arrangement, void volume and soil type on drainage using a physical model.

First the specific yield for a typical hazardous waste site using leachate level and production data was determined. The specific yield was calculated for a set of data collected at a commercially operated hazardous waste site, containing drums and bulk waste. This information was obtained through the Region II Office of the U.S. Environmental Protection Agency. The leachate level information obtained from the commercial site was highly variable (large day-to-day fluctuations in leachate level), so estimates of specific yield had a large amount of uncertainty associated with them. Because the data from the commercial site were so variable, a second site was selected in hopes of collecting more usable data. An automatic data logging system was installed to measure leachate level at hourly intervals. The leachate level information was used to estimate specific yield for this site. In addition, changes in leachate levels were related to precipitation and barometric pressure changes.

Specific yield can be estimated at sites using three approaches. If large void volumes can be estimated and are believed to be predominant in the waste, then specific yield is calculated, ignoring the drainage contributions of bulk materials (Example Case 2 in Section 5). When large voids are present with draining bulk material, the specific yield of both can be combined for an overall specific yield (Example Case 3 in Section 5). A third approach is to use the specific yield measured at a hazardous waste site of similar design and waste composition. Unfortunately, specific yield values for hazardous waste sites could not be found in the literature.

Specific yield estimates are thought to be affected by the amount of barrel arrangement, void volume, and backfill soil type. To demonstrate the importance of these variables, a physical model representing a portion of a hazard waste landfill was constructed, and drainage information collected from this model is discussed in this section.

SPECIFIC YIELD ANALYSIS FOR THE COMMERCIAL SITE

Data from a hazardous waste landfill site located in a humid environment were analyzed. The site has many waste cells, and each cell is designed to minimize leachate migration into the surrounding environment. The cells are excavated in native clay and lined with both compacted clay and flexible membrane liners. Figure 6.1 illustrates the general plan of each of the subcells in the cell where data used in this analysis were collected. This cell is divided into five subcells; each subcell is hydraulically separated using clay berms to allow the segregation of certain types of hazardous wastes.

The data collected by the facility operator consisted of daily leachate level measurements in standpipes for each subcell and monthly total leachate volumes pumped from each cell. Two leachate levels were recorded for each day for each subcell: the level measured before pumping started and the level measured immediately after pumping stopped. Leachate levels were measured in standpipes using a weighted string, and pumping volumes were measured using totalizing flow meters. Because of large variations in day-to-day leachate level measurements, all calculations performed in this report used the maximum measured leachate level for each month.

To collect leacate generated during the landfilling operation, leachate collection networks were located in each subcell. Each network consisted of

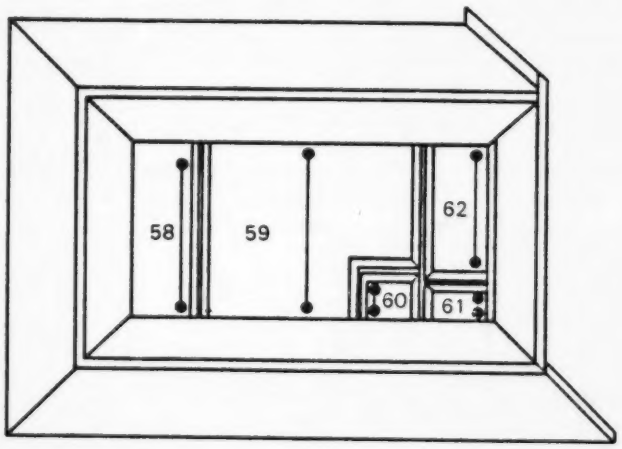


Figure 6.1. Plan view of Cell.

two perforated concrete standpipes connected to one another by a perforated 0.10-m clay pipe. The standpipes were constructed as the subcell was filled, so that at no time did the standpipe extend more than 1.21 m above the working floor of the landfill. The bottom liner was sloped toward each standpipe to facilitate drainage. Leachate was pumped from one standpipe in each subcell, and the leachate level was measured daily in each standpipe.

Waste in each of the cells consisted of both bulk (e.g., sludges, contaminated soils) and drummed (e.g., 0.21-m^3 drums) material. Drums were stacked upright as closely together as possible. Sludge waste material was unloaded into a bermed area built to accept the amount of material coming in on a particular day. Bulk waste material was also placed in each cell using a front-end loader. Landfill operators estimated a volume ratio of two parts bulk waste to one part drummed waste existed in the cell. At the end of each daily shift, at least 0.15 m of cover material was placed over all exposed drums. This cover material ranged from natural clays and sands to neutralized wastewater sludges. On completion, the cell was covered with a minimum of 0.91 m of compacted clay, 0.45 m of uncompacted clay or clay/soil mixture, and 0.15 m of top soil, and then seeded with perennial rye and bluegrass. This was a temporary cover.

The cell received waste from the summer of 1979 to the fall of 1982, when the above cover was installed to reduce infiltration. Final closure was completed in September 1983. Leachate was removed from the standpipe collection system during cell operation using a portable pump and/or vacuum trucks. Beginning in February 1984, an automatic pumping system was installed that consisted of sump pumps actuated by leachate level.

Results for the Commercial Site

The analysis focused on interpreting the existing leachate production data from the cell to determine the hydraulic properties of the waste material. To analyze the leachate production from a mixed-waste disposal site, leachate level data were used to estimate the specific yield or drainable porosity. These data are extremely important because they can be used to estimate the total amount of drainable leachate in the landfill. In estimating the specific yield, the leachate level in the landfill was assumed to have reached equilibrium when the monthly maximum value occurs. In cases where the leachate pumping rate was small in comparison to the volume of leachate contained in the landfill, the assumption of instantaneous drainage appears valid. With small daily changes in leachate level, the contribution to drainage from unsaturated soils is relatively constant as the pressure head throughout the unsaturated backfill and waste decreases slowly. Therefore, the change in leachate level is primarily a function of large pores and/or voids in the waste which drain rapidly.

The temporary cap was assumed to have significantly reduced fluid input to the cell. This being the case, fluid input to the cell would be negligible, and the leachate level taken after September 1982 should have been primarily influenced by leachate pumping. The data indicate that the volume of leachate pumped declined rapidly after the temporary cover was installed in September 1982. Table 6.1 shows the monthly maximum leachate

TABLE 6.1. MONTHLY MAXIMUM LEACHATE LEVEL AND VOLUME FROM PUMPED SUBCELLS OF THE CELL

Date	Subcells (m)*										Total m^3 pumped
	#58	#58A	#59	#59A	#60	#60A	#61	#61A	#62	#62A	
Sep 82	7.01	7.07	2.62	2.23	1.43	1.83	1.92	1.89	2.68	6.77	363.40
Oct 82	6.92	6.07	2.87	2.96	1.40	1.43	1.92	1.98	5.49	7.77	155.58
Nov 82	6.49	6.52	1.89	1.68	1.40	1.55	1.92	1.74	7.07	3.14	185.49
Dec 82	...	...	...	...	...	...	...	...	...	...	147.63
Jan 83	6.95	6.71	2.50	2.38	1.43	1.52	1.52	1.58	4.39	7.04	111.81
Feb 83	6.52	6.25	2.87	2.93	1.34	1.25	1.43	1.28	3.78	6.74	109.68
Mar 83	...	...	...	...	...	...	...	...	...	...	90.85
Apr 83	...	...	...	...	...	...	...	...	...	...	90.85
May 83	5.55	4.57	1.68	2.56	1.07	1.52	1.71	1.58	7.35	6.04	72.65
Jun 83	5.73	4.45	1.77	1.49	1.37	0.98	1.40	1.58	3.84	6.64	60.51
Jul 83	5.73	4.57	1.71	1.80	0.85	1.46	1.49	1.40	2.53	5.91	120.52
Aug 83	5.00	4.60	0.79	1.13	2.38	3.81	1.22	1.68	1.95	4.54	81.88
Sep 83	4.51	4.48	0.46	1.07	0.46	0.52	1.10	1.58	1.55	3.51	58.67
Oct 83	4.15	3.29	0.30	0.73	0.34	0.43	0.85	0.98	1.49	2.83	46.61
Nov 83	4.08	3.35	0.49	1.13	0.49	0.30	0.52	0.76	1.04	2.74	38.20
Dec 83	3.99	3.60	1.16	0.67	0.40	0.34	0.61	0.76	2.04	2.47	36.93
Jan 84	3.87	3.54	0.88	0.55	0.43	0.40	0.64	0.67	1.77	2.07	37.01

* (1 meter = 3.2808 ft)

levels in each of the five subcells. These data show decreasing leachate levels in response to leachate pumping. Table 6.1 also indicates that the leachate levels in all but Subcell #62 decreased at a nearly constant rate, whereas the leachate production rate dropped off in an exponential fashion.

One possible cause for the linear decline in the leachate level was due to the variable geometry of each subcell as it drained. Because the sidewalls of the cell slope, removing a given volume of leachate at high leachate levels will not lower the level as much as when the leachate level is low. If the cell walls were vertical, the decline in leachate level would be directly proportional to the leachate production rate. Given the sloping sidewall, however, a nonlinear behavior in the leachate level/production ratio is expected. To produce the linear trend in leachate level found in each subcell of the cell, a leachate production rate that decreases with time is required (see Table 6.1). A second possible cause of the trend toward a linear decline in the leachate level may be changes in equilibrium conditions with landfill depth.

To help evaluate these two possibilities, the specific yield was calculated over two time periods. The first time period was from September 1982 to September 1983, the second from October 1983 to January 1984. The first of these periods reflects the time during which the temporary cover was in

place. The second period covers the time the final cover was in place. Specific yield, cover integrity, and changes in waste void ratios are evaluated in relation to data from these time periods.

If cover leakage occurred from September 1982 to September 1983, the specific yield calculated during temporary closure would be higher than that calculated after permanent closure. The higher specific yield would be a result of infiltrating water offsetting the reduction in the leachate level brought about by pumping. Also, the question of equilibrium conditions can be answered. If leachate levels in the standpipe are lower than the actual waste leachate level, then the specific yield calculated during this time would be lower (less fluid drained from a unit decline in head) than that calculated when equilibrium conditions existed.

Using data from Table 6.1 and the subcell volume equations located in Appendix A, the total saturated cell volume in September 1982 of 47,969 m^3 can be calculated. In September 1983, the saturated cell volume was calculated at 22,782 m^3. The total leachate volume pumped from September 1982 to September 1983 was 1,649 m^3. The resulting specific yield is calculated as

$$S_y = \frac{\text{volume of leachate removed}}{\text{landfill volume drained}} \qquad (6.1)$$

$$S_y = \frac{1{,}649\ m^3}{47{,}969\ m^3 - 22{,}782\ m^3}$$

$$S_y = 0.065 \text{ or } 6.6\%$$

The same method was used to determine the specific yield during the period from October 1983 to January 1984. The total leachate volume pumped during this period was 158 m^3. The specific yield is calculated as

$$S_y = \frac{158\ m^3}{18{,}340\ m^3 - 16{,}893\ m^3}$$

$$S_y = 0.11 \text{ or } 11.0\%$$

The results of these analyses indicate that the specific yield was 6.6% during the first time period and 11.0% during the second time period. This change in specific yield may be real or an error associated with selecting the monthly maximum leachate level as most representative of leachate level change in response to pumping.

Assuming the increase in specific yield is real, the rise in the specific yield value is most likely the result of the inhomogeneities of the wastes and the subcell variations hidden by averaging the saturated waste volumes. Alternate explanations are 1) the permanent cover is less effective than the temporary cover or 2) leachate levels

measured during September 1982 through September 1983 may not have been at equilibrium (possible since the volume pumped per month is relatively large).

The specific yields determined in this analysis suggest only an averaged value over the entire cell. They do, however, represent a range of values for this type of waste. Approximately two-thirds of the cell volume is estimated to contain soil or bulk waste with the remainder containing no drainable porosity (e.g., drum transformers). If the entire landfill contained bulk wastes, the specific yields calculated above would be increased by 50%. Therefore, the specific yields can be increased from 6.6% and 11% to 10% and 17% for the two time periods investigated. These figures are in the same range as those reported for municipal waste. Specific yields reported for municipal waste range from 12% to 21% (Fungaroli 1971; Straub and Lynch 1982). Therefore, it may be possible to estimate specific yield or drainable porosity of hazardous waste landfills from existing data for municipal waste with a reduction factor accounting for the volume of waste containing no drainable porosity (e.g., drums, transformers) as determined from waste inventories.

SPECIFIC YIELD ANALYSIS FOR GLEN FALLS, NEW YORK

A field site was selected to collect leachate level information continuously using an automatic water level recorder. This information was compared with leachate levels manually collected at the commercial waste site described in the previous discussions. The selection criteria for the site required that the leachate be removed in known quantities, at regular intervals, and that leachate levels be measured with automated equipment. This information is necessary to estimate specific yield for a mixed-waste site. It was hoped that leachate level information collected in this manner would not suffer from the high variablility associated with the data from the commercial site. In addition to specific yield information, this field effort has provided information on the collection and reliability of remote sensing of water level data, effects of precipitation on infiltration rate, and atmospheric-pressure-induced changes in leachate levels.

This site is located in Glen Falls, New York, approximately 87 km north of Albany, New York, in central New York State. The site contains electrical transformers of various sizes and sandy soil contaminated with transformer oil. The soil is classified as a sand and contains 90% sand, 7% silt, and 3% clay. This waste site has an ineffective clay cap, which was originaly scheduled for replacement during the summer of 1984, but has not yet been replaced. The liner is constructed from two layers of clay separated by gravel with a leak detection system located in the gravel. Figure 6.2 represents a cross-sectional view of one-half of the waste site. The waste site has a base area of 15.4 m by 66.75 m, and each side wall has a slope of 3:1. The landfill is approximately 5.5 m deep at its center. The surface area of the waste site is 3314 m^2, and it is covered with vegetation, predominantly grasses. The automated water level recorder, (shown in Figure 6.3) uses a float and wire-driven encorder wheel to measure

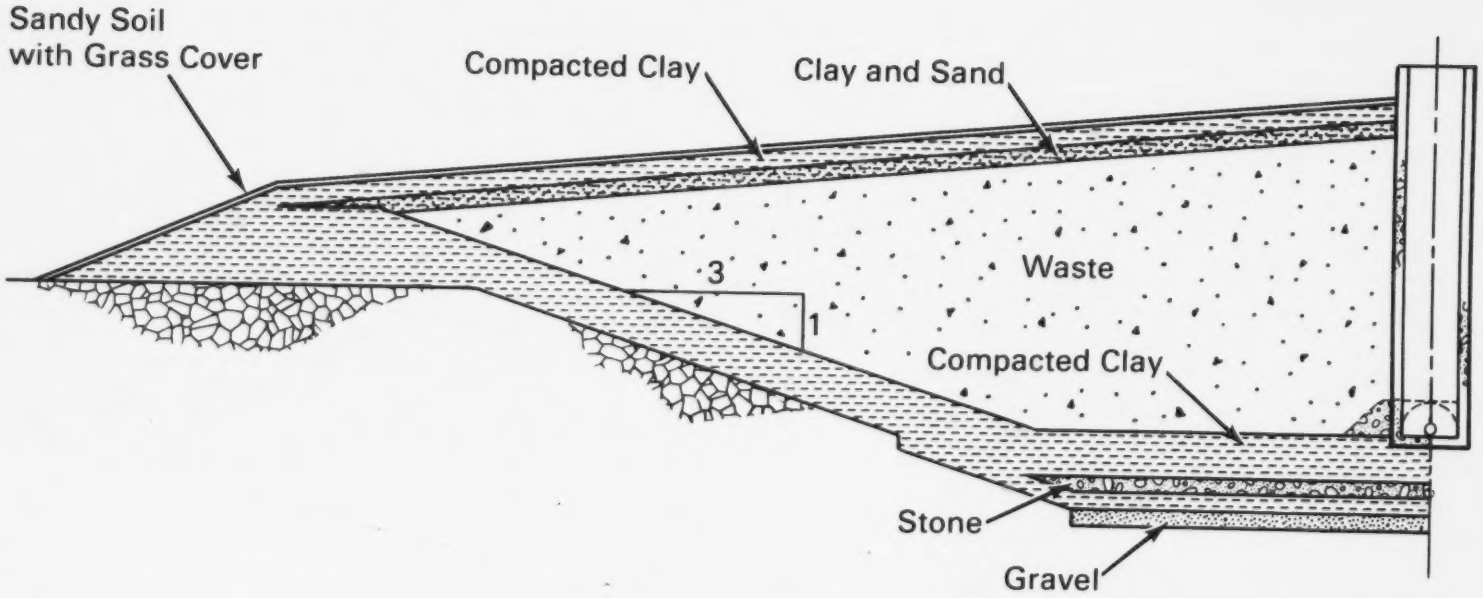


Figure 6.2. End view of waste site at Glen Falls, New York.

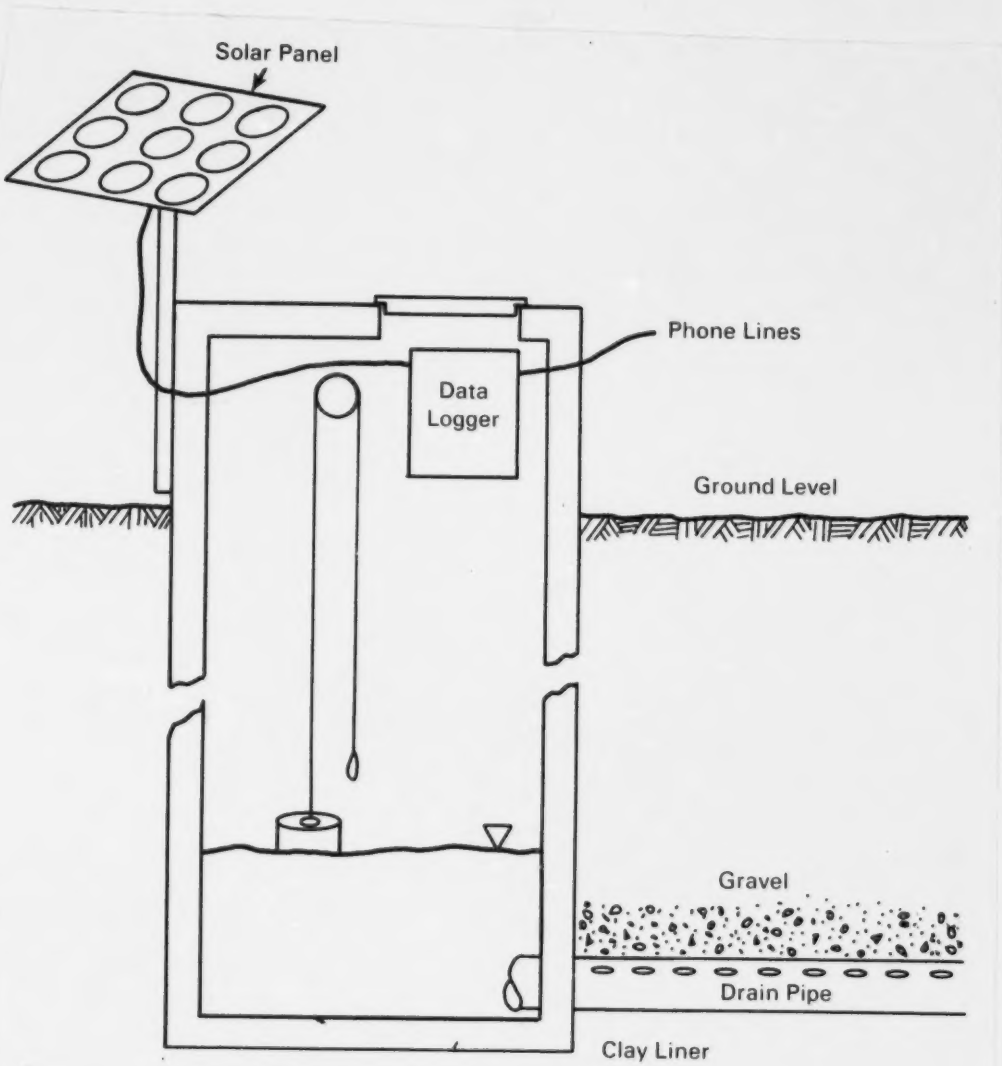


Figure 6.3. Leachate level measurement system.

leachate levels to ±0.3 cm. Data were recorded hourly on magnetic tape and stored in memory for weekly interrogation by computer over a telephone line modem.

The leachate level was monitored intermittently for a few days in May and June of 1984 and continuously during September, October, and November of 1984 (see Figure 6.4) as leachate was removed from the waste site in 25.0-m^3 increments. In addition, data on the leachate levels were also collected during December 1984 and January 1985 after pumping ceased because of freezing temperatures and snow.

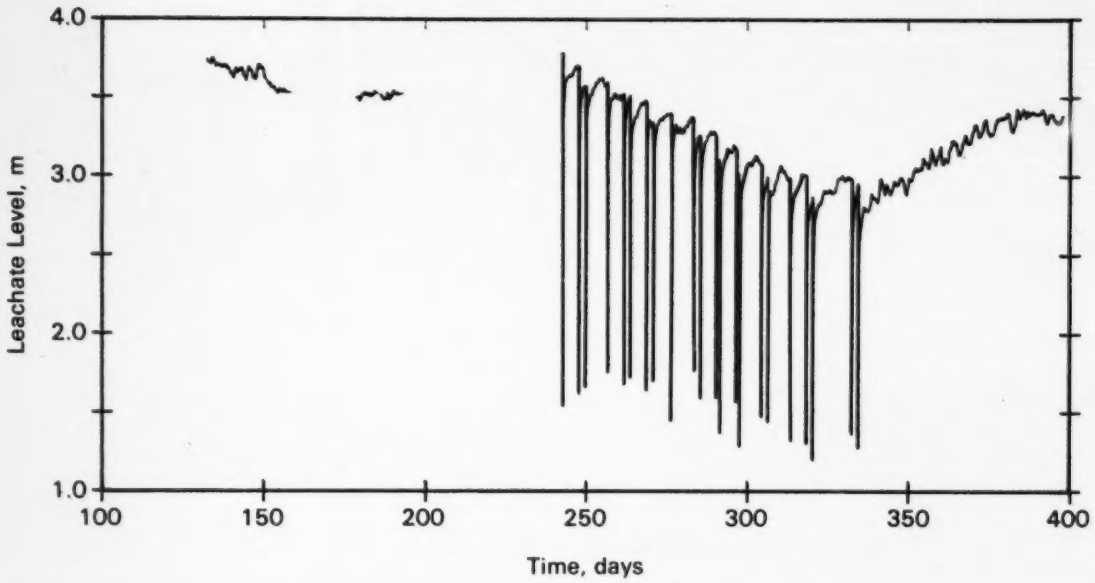


Figure 6.4. Leachate levels in hazardous waste site at Glen Falls, New York.

Precipitation data were obtained for Glen Falls, New York, and values of atmospheric pressures were obtained for Albany, New York (NOAA 1985).

Specific yield was determined by dividing the amount of leachate removed during pumping by the soil volume drained. The cross-sectional surface area (WS_{area}) at any vertical level in the waste site can be calculated using Equation 6.2. As the leachate level changes, a maximum and minimum surface area are averaged and then multiplied by the amount of vertical water level change. This product is an approximate volume of the waste site drained.

$$WS_{area} = [(LL \cdot 6) + 15.4] \cdot [(LL \cdot 6) + 66.75] \quad (6.2)$$

where LL is the leachate level.

A specific yield was calculated for leachate removal occurring during September, October, and November of 1984. The leachate level in the well is not always at equilibrim with the leachate level in the waste site. This can be observed in Figure 6.5, where pumping events seperated by only one day have truncated recharge curves. Individual estimates of specific yield vary considerably if leachate levels are not in equilibrium with levels in the waste. All pumping events can be grouped to minimize errors associated with nonequilibrium conditions. A specific yield was obtained by dividing the total leachate volume removed by the volume of the waste site drained,

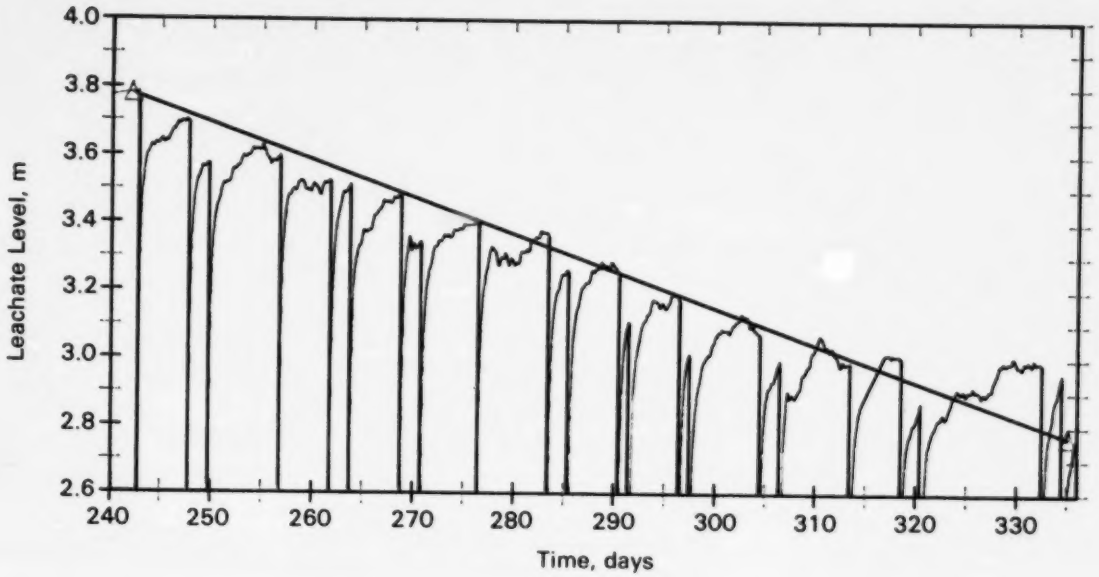


Figure 6.5. Leachate levels during pumping of waste site at Glen Falls, New York.

using a starting and ending leachate level of 3.78 m and 2.77 m, respectively. These two points are connected by a straight line on Figure 6.5, which intercepts most of the recovery leachate levels occurring after pumping. This indicates minimal infiltration except at the end of November 1984. The specific yield calculation for this time period follows:

Surface area, A, with leachate level at 3.78 m:

$$A \text{ (day 243)} = [(3.78 \text{ m} \cdot 6) + 15.4 \text{ m}] \cdot [(3.78 \text{ m} \cdot 6) + 66.75 \text{ m}) = 3405 \text{ m}^2.$$

Surface area, A, with leachate level at 2.77 m:

$$A \text{ (day 336)} = [(3.77 \text{ m} \cdot 6) + 15.4][(2.77 \text{ m} \cdot 6) + 66.75 \text{ m}] = 2670 \text{ m}^2$$

$$A_{ave} = \frac{3405 \text{ m}^2 + 2670 \text{ m}^2}{2} = 3037 \text{ m}^2$$

The leachate volume, L_{vol}, removed is:

$$L_{vol} = 22 \text{ pumping events} \cdot 25 \text{ m}^3 \text{ leachate vol/event} = 550 \text{ m}^3 \quad (6.3)$$

Then the specific yield, S_y (from Equation 5.1) is

$$S_y = \frac{550\ m^3}{3037\ m^2 \cdot (3.78\ m - 2.77\ m)}$$

$$S_y = \frac{550}{3067} = 0.18$$

The specific yield calculated for the site was used to estimate infiltration that occurred when pumping ceased from December 1984 through January 1985. Leachate levels measured during this time showed a cyclic rise and fall and a long-term baseline increase in level. This increase is attributed to precipitation infiltrating the surface cover. Changes in leachate levels of 0.1 m were observed in a 24-hr period when barometric pressures fluctuated by 1.47 cm of Hg. The cyclic changes in leachate levels appear to be inversely correlated to atmospheric pressure during the winter months (Figure 6.6). Decreases in water level generally coincide with increases in atmospheric pressure. The literature notes an inverse relation between atmospheric pressure and water level for unconfined shallow aquifers or lysimeters (Turk 1975 and Van Hylckama 1968).

The leachate level increased during December 1984 by 0.43 m, from 2.77 to 3.20 m, and in January 1985 by 0.2 m, from 3.2 to 3.4 m (see Figure 6.6). Precipitation during December 1984 and January 1985 was 12.6 and 3.8 cm, respectively. These values can be used to calculate the percentage of precipitation that infiltrated into the landfill. The volume of precipitation available to enter the landfill, P_{vol}, is the product of rainfall (RF) and surface area (A):

$$RF \cdot A = P_{vol} = .126\ m \cdot 3314\ m^2 = 418\ m^3 \qquad (6.4)$$

The measured volume of the landfill, LF_{vol} (measured), saturated by infiltrating rainfall, can be computed with the following equation:

$$LF_{vol}\ (\text{measured}) = WS_{ave} \cdot \Delta h \qquad (6.5)$$

where Δh is the change in saturated depth and WS_{ave} is the average of the saturated waste area. WS_{ave} is computed as follows:

$$WS_{day\ 336} = 2670\ m^2$$

$$WS_{day\ 400} = \lfloor(3.20 \cdot 6) + 15.4\rfloor \lfloor(3.20 \cdot 6) + 66.75\rfloor = 2974\ m^2$$

$$WS_{ave} = \frac{2670\ m^2 + 2974\ m^2}{2} = 2822\ m^2$$

then

$$LF_{vol}\ (\text{measured}) = 2822\ m^2\ (3.20\ m - 2.77\ m) = 1213\ m^3$$

The percentage of rainfall infiltrating, I, is calculated as follows:

$$I = \frac{LF_{vol}\ (\text{measured})}{\frac{P_{vol}}{Sy}} = \frac{1213\ m^3}{\frac{418\ m^3}{.18}} = .52 = 52\% \qquad (6.6)$$

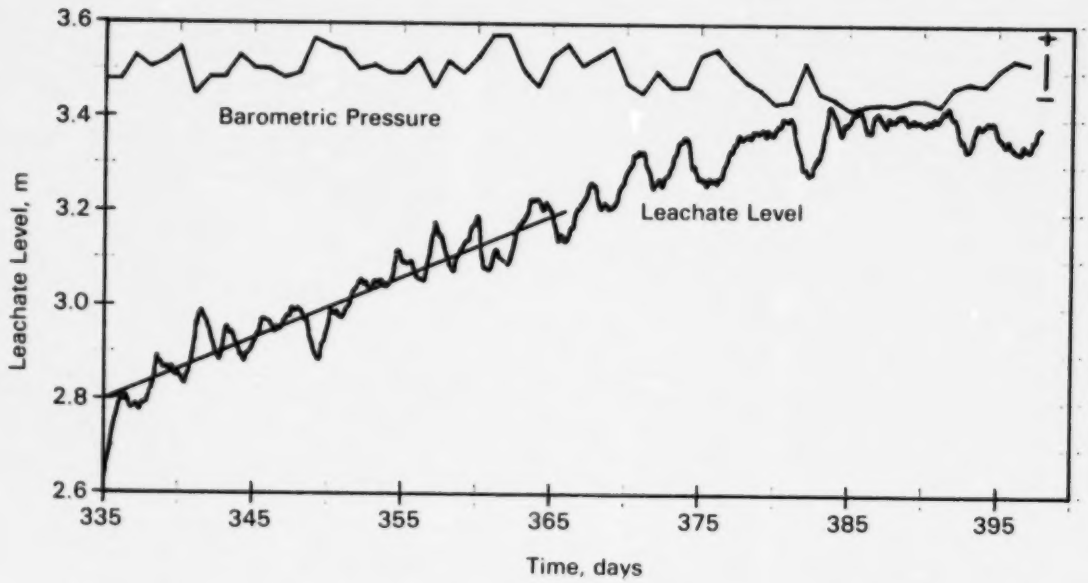


Figure 6.6. Comparison of leachate levels to atmospheric pressure.

The actual waste site volume saturated during December 1984 is 52% of the potential volume that would have been saturated if all precipitation entered the waste site. Note that infilitration associated with individual precipitation events in December cannot be directly inferred from increases in leachate level because much of the precipitation falls as snow. Most of the precipitation during January fell as snow and did not melt; therefore, no calculation of infiltration for the month of January is provided. In addition, atmospheric pressure changes may mask changes in leachate level caused by infiltration.

Total precipitation for September, October, and November was 0.17 m. From the previous data, it is obvious that precipitation infiltrated the landfill cover. The specific yields calculated during the pumping event in September, October, and November do not account for infiltration. Precipitation volume available for infiltration during these months was calculated as follows:

$$P_{vol} = 0.170 \text{ m} \cdot 3314 \text{ m}^2 = 563 \text{ m}^3$$

Assuming a worst case, where the same 52% of rainfall infiltrated in September, October, and November as did in December, the infiltration volume, P_{infil}, would be

$$P_{infil} = 0.52 \cdot 563 \text{ m}^3 = 292 \text{ m}^3$$

If 292 m^3 of the 550 m^3 of leachate removed during pumping was from infiltration of precipitation, then the specific yield would be as follows:

$$S_y = \frac{550\ m^3 - 292\ m^3}{3067} = 0.08$$

Evapotranspiration would have been higher during the September to November period than during December. Therefore, the actual specific yield is most likely somewhere between 18% and 8%.

Summary of Results for Glen Falls, New York

This field monitoring program was directed at measuring the specific yield of a hazardous waste site as it drained. It was assumed previously that this site had a leaking cover (cap) through which rainwater infiltrated, but there was little documentation to quantify amounts.

From the data, a specific yield of 18% was calculated. This estimate may be high because the volume of waste drained may be underestimated; part of the water removed during pumping may have infiltrated the landfill during the 3-month pumping period. These contributions to leachate volume by infiltrating precipitation would have decreased the waste volume drained. A specific yield of 8% was calculated as a conservative estimate of specific yield assuming that 52% of precipitation entered the landfill.

The feasibility of using an automatic data logging system for collecting continuous records of water level data was demonstrated. This continous record of the water level permitted monitoring of the response of the leachate level to 1) pumping events, 2) precipitation, and 3) barometric pressure fluctuations.

In addition, the use of the data acquistion system has pointed out the potential for measurement errors when intermittent manual readings are taken. For example leachate levels measured in the well are a function of the leachate level in the waste material and the barometric pressure; thus, a single daily reading will not reflect changes in leachate levels resulting from barometric changes (we observed changes in leachate level to be as large as 0.1 m in a 24-hr period when pressures fluctuated by 1.47 cm of Hg).

Measurement of leachate levels in closed waste sites can be extremely useful in evaluating the integrity of the cap and liner materials. For remote or hazardous sites where daily observations of leachate level are not practical, use of automatic data logging systems should be considered. Modern data logging systems can record water levels at selected intervals, record the information, and/or transmit the information over telephone lines. If detailed analysis of small magnitude changes in water level are attempted, corrections must be made for changes in atmospheric pressure.

Data logging systems are available that can measure both water level and atmospheric pressure in a remote locations and transmit the information via telephone lines or orbital satellite relay.

SPECIFIC YIELD ANALYSIS FOR THE PHYSICAL MODELS

Hazardous waste landfills often contain a heterogeneous mixture of materials. The waste forms may consist of barrels or drums and other solid objects (e.g., plastic buckets, trtansformers) stacked or placed in random fashion in the waste cell. In addition, the backfill materials may be local soils or finely divided, bulk waste materials. Solid objects in the wastes do not contribute to drainage but can be surrounded by significant void volume. When landfills contain heterogeneous materials and have a large amount of void volume, predicting the drainage performance and leachate production of the waste cell is difficult. The drainage from a hazardous waste landfill can be estimated, however, by carefully assessing the physical parameters such as barrel arrangement, void volume, and soil backfill type.

Physical models were constructedc to represent various configurations of drummed waste and backfill materials. Barrel arrangement, interbarrel void volume, and backfill soil properties were evaluated by simulating a section of landfill containing 8 to 10 barrels, each 0.21 m^3, and backfill soil material. Table 6.2 shows the treatment combinations evaluated and indicates the appropriate diagram in Figure 6.7. The horizontal double-layer barrel arrangement was modified to maximize barrel volume within the tank, while maintaining the layer effect under investigation.

For each physical model constructed, the barrel volumes, and large interbarrel void volumes were calculated. Drainage was measured by continuously weighing the entire model. Drainage rates from the physical model were restricted by the outflow pipe conductivity and the soil column flow resistance. Drainage rates at any time were determined as a function of the outflow pipe resistance, treatment-dependent soil resistance, and

TABLE 6.2. DRAINAGE TEST CONFIGURATION AND DESCRIPTIONS

Treatment Description	Figure
Coarse sand, no barrels	Not Shown
Coarse sand, single layer, barrels, voids	b
Coarse sand, single layer, barrels, no voids	b
Coarse sand, double layer, barrels, no voids	c
Coarse sand, vertical, barrels, voids	a
Coarse sand, vertical, barrels, no voids	a
Fine sand, single layer, barrels, voids	b
Fine sand, single layer, barrels, no voids	b

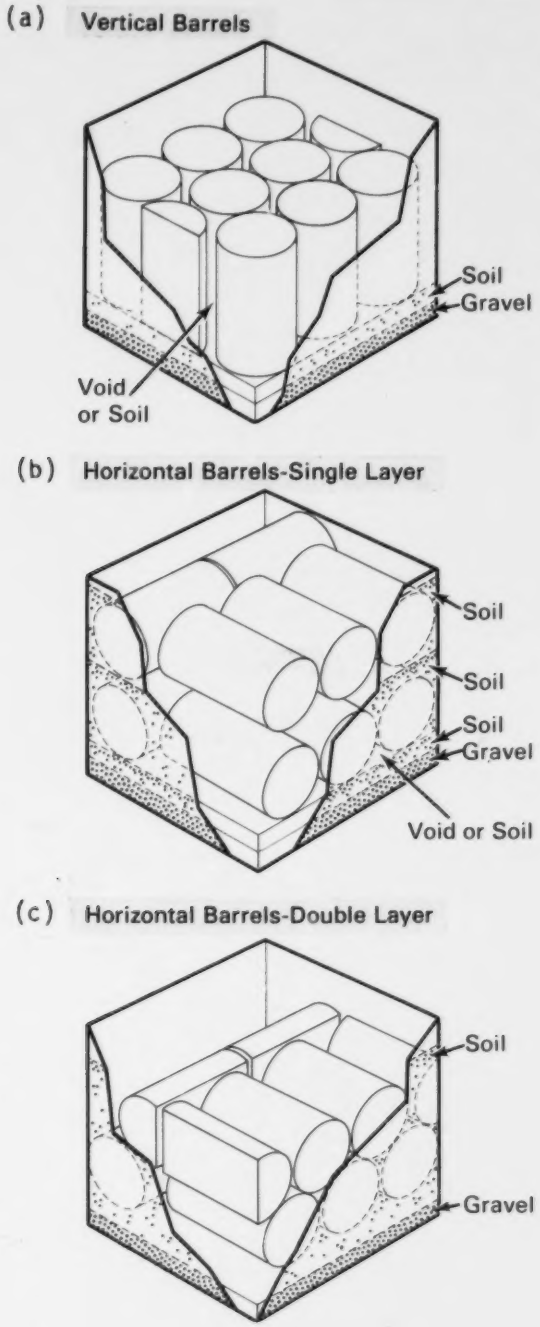


Figure 6.7. Diagram of physical model treatments.

hydraulic head of the saturated soil column inside the model. The configurations tested are representive of a waste site volume that drains vertically to a drain field. After entering the drain field, the leachate

is transported horizontally to a pumping station that maintains a negligible head at a well point. Leachate flow in the physical models is initially limited by the pressure head and the conductivity of two 4-cm drain pipes until the soil column drainage rate falls below this flow-inhibiting factor.

Physical Model Construction

All physical models were constructed inside an open-top steel tank with dimensions of 1.52 x 1.82 x 1.67 m in height, width, and length, respectively. The tank was located on a platform scale with 9,100 kg capacity. The data collection equipment is shown in Figure 6.8. A gravel and geotextile layer, 0.1 m thick, was placed on the bottom of the tank. The tank was filled from the bottom by pumping water into the gravel layer. Drainage waters were released through pipes located in the layer.

Three major barrel arrangements were investigated and are shown in Figure 6.7. These included two single layers of barrels separated by soil (Figure 6.7b), a single layer, two barrel layers thick (Figure 6.7c) and a vertical arrangement of the barrels (Figure 6.7a). The second two of the three configurations required partial barrels constructed by cutting barrels to the desired size and filling them with cement to maintain a volume not contributing to drainage. Two different soils, a sand and a

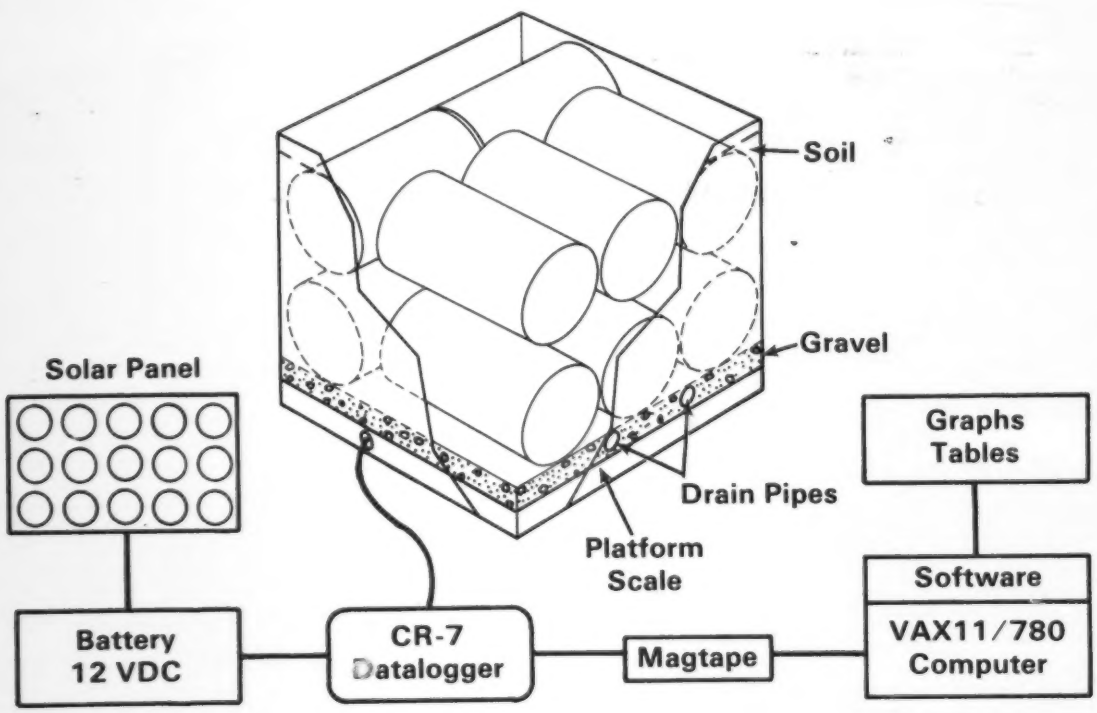


Figure 6.8. Data collection system for drainage studies.

loamy sand, were used as backfill. Values of saturated conductivity, particle size distribution, and water retention characteristics are described in Appendix B for these soils.

In all treatments, a 10-cm soil layer was placed over the geotextile gravel layer located in the tank bottom. The first layer of barrels was then placed inside the tank. If the treatment called for no large voids, soil was packed into all spaces between barrels. If the treatment required voids, a geotextile was placed over the barrels to prevent backfill soil from falling between the barrels. The maximum vertical dimension of the soil and barrels inside the tank was 1.32 m.

Results for the Physical Models

The specific yield for the entire tank, measured for each treatment is dependent on the presence of large void volume, soil volume available for drainage, soil drainage characteristics, and the amount of soil column discontinuities introduced by void volume. Values for total drainage, barrel volume, large void volume, specific yield, maximum drainage rate, and time required for drainage rate to decrease below an arbitrarily chosen flux of 5.46×10^{-4} cm/s for each treatment are presented in Table 6.3. Calculation of specific yield for all treatments is based on the average leachate volume drained from that treatment divided by the filled volume of the tank as shown:

$$\text{Specific yield} = \frac{\text{leachate vol}}{\text{soil and barrel vol}^*} \qquad (6.6)$$

* For all treatments soil and barrel volume = 4.03 m^3

Calculation for the sand, single layer, and no voids treatment is

$$\text{Specific yield} = \frac{430{,}160\ cm^3}{4{,}030{,}000\ cm^3} = 0.11$$

Specific yield for the entire tank is largest when large void volumes are present. Conversely, the lowest specific yields are reached when no large void volumes exist. The specific yield for the treatment using sand and no barrels (0.24) is only slightly less than the values for the treatments using loamy sand, single layer, and large voids (0.28) and using sand, single layer, and large voids (0.28).

In Section 5, it was proposed that specific yield would be controlled by the amount of large void volume in the waste site. If estimates had been used for void volumes of the sand, single layer, and voids (0.77 m^3) and of loamy sand, single layer, and voids (0.90 m^3) as the only significant contribution to drainage, specific yields of .19 and .22, respectively, would have been estimated. It appears that accurate estimates of void volumes and

TABLE 6.3. TREATMENT SUMMARY INFORMATION

Treatment	Average Drainage (kg)	Barrel Volume (m^3)	Large Void Volume (m^3)	Specific Yield Tank	Maximum Drainage Rate (cm/s)	Time (min) Elapsed Until Drainage Falls Below 5.46×10^{-4} cm/s
Sand, No Barrels	987.2	-0-	-0-	0.24	4.46×10^{-2}	105
Sand, Single Layer, No Voids	430.2	2.08	-0-	0.11	1.74×10^{-2}	47
Sand, Vertical, Voids	666.0	1.87	0.35	0.17	2.90×10^{-2}	37
Sand, Vertical, No Voids	536.4	1.87	-0-	0.13	2.06×10^{-2}	50
Sand, Single Layer Voids	1130.5	2.08	0.77	0.28	6.52×10^{-2}	26
Sand, Double Layer, No Voids	467.4	1.98	-0-	0.12	2.38×10^{-2}	51
Loamy Sand, Single Layer, No Voids	238.8	2.08	-0-	0.06	8.92×10^{-3}	202
Loamy Sand, Single Layer, Voids	1125.0	2.08	0.90	0.28	4.67×10^{-2}	38

the drainage contribution of the backfill soil will be required to predict reasonable values of specific yield from sites with sandy backfill materials. When fine soils are used as backfill material, much less water drains out of the soil and predicting specific yield using only the void volume may be reasonable.

The specific yield values for the loamy sand are lower than those for the sand even though soil porosity is greater for the loamy sand. The water retention curves (Appendix B) for the loamy sand and sand illustrate

graphically the greater amounts of water retained by the loamy sand compared to the sand at any pressure head. Figure 6.9 shows the changes in weight associated with filling and draining two treatments: sand, single layer, and voids; and loamy sand, single layer, and voids. Almost all of the water added to the coarse sand drained out. The loamy sand retained approximately 20% of the water added.

Soil moisture samples taken as the treatments were installed and removed confirm the storage of water. Initial soil water contents (g/g) were 3% for the sand and 7% for the loamy sand; ending moisture contents for the surface soil layer were 7% at the surface and 15% above the geotextile in the sand and 24% at both levels in the loamy sand.

Drainage rates and amounts varied according to waste configuration. Cumulative drainage curves generated for each treatment indicate the decreasing drainage rate with time. The drainage curves from selected treatments are compared in the following five figures (Figures 6.10 to 6.14). Multiple lines with the same symbols represent replicate filling-draining cycles of each treatment. The observed initial drainage rates and duration of drainage as influenced by treatment are of interest as indicators of how long actual waste sites may take to drain. Figure 6.10 compares the treatment using sand and no barrels with the treatment using sand with single layer barrels. As expected, the total drainage is less for the sand with barrels treatment because approximately half of the treatment volume consists of barrels, which do not contribute to drainage. Also note that the presence of barrels in sand causes the maximum drainage rate to be less (a result of the longer flow path around the barrels) (see Table 6.5) and the drainage rate to decrease sooner because the pressure head drops faster (Figure 6.10).

Stacking the barrels in multiple layers should increase the number of barrels that can be disposed of within any given volume. The treatment using sand, double layer, and no voids has two layers of closely packed barrels. Size limitations of the tank forced the use of partial barrels with a resultant barrel volume (2.0 m^3) slightly less than the single layer (2.1 m^3). Figure 6.11 indicates little difference in the drainage rates or duration of drainage. The maximun drainage rate was slightly higher in the double-layer treatment--2.38×10^{-2} cm/s versus 1.74×10^{-2} cm/s--but the time required for the drainage rate to decrease below 5.46×10^{-4} cm/s was almost equal: 51 min and 47 min for the double layer and single layer, respectively.

Vertical placement of barrels is common and has the potential for being the easist way to eliminate void spaces during backfilling operations. The estimated void area is approximately half of the possible interbarrel space because of subsidence during the first drainage run with this treatment. Figure 6.12 shows that the drainage from vertical barrels with voids was greater than drainage from vertical barrels without voids. Therefore, the tank specific yield is higher for the vertical barrels with voids than that for the vertical barrels without voids.

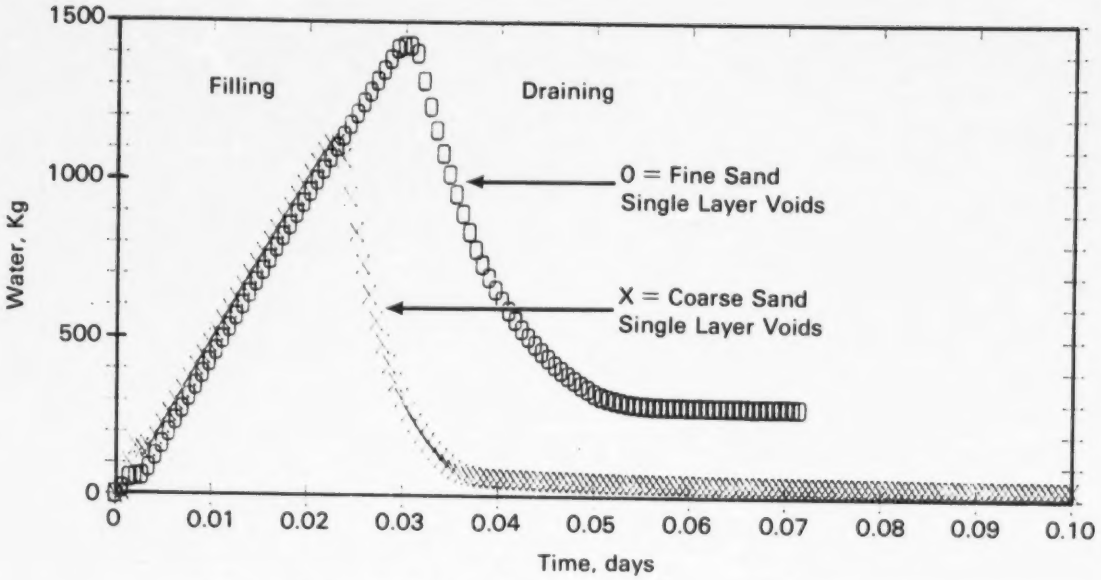


Figure 6.9. Water retention in loamy sand and sand.

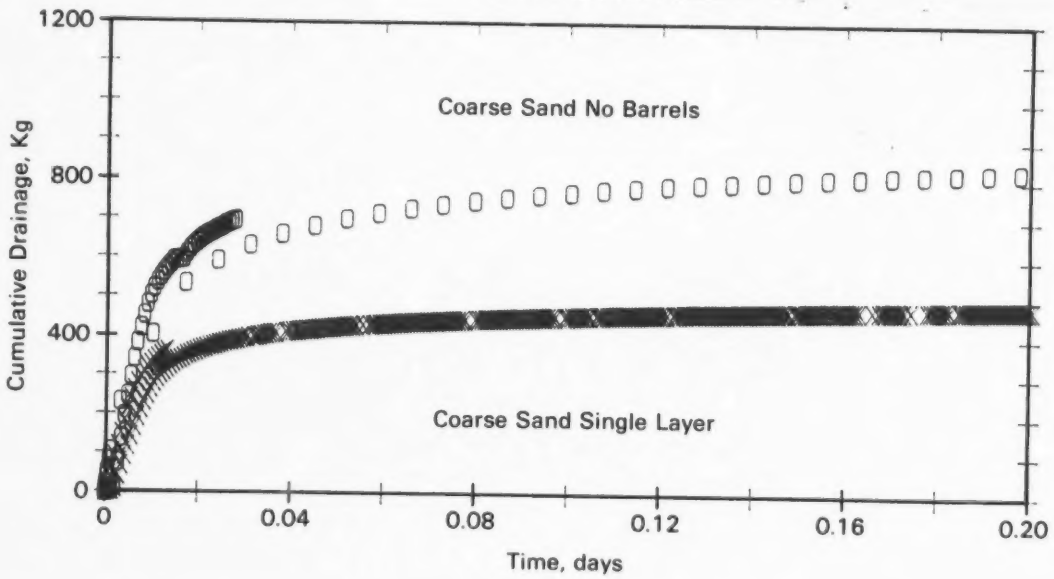


Figure 6.10. Comparison of the effect of barrels on cumulative drainage rates in sand.

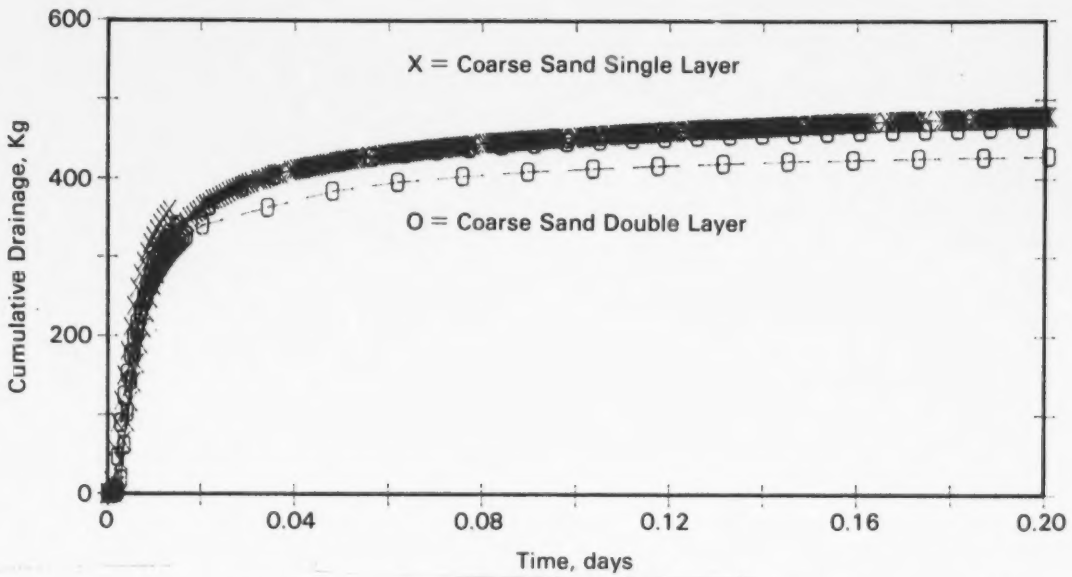


Figure 6.11. Comparison of the effects of barrel layering on cumulative drainage in sand.

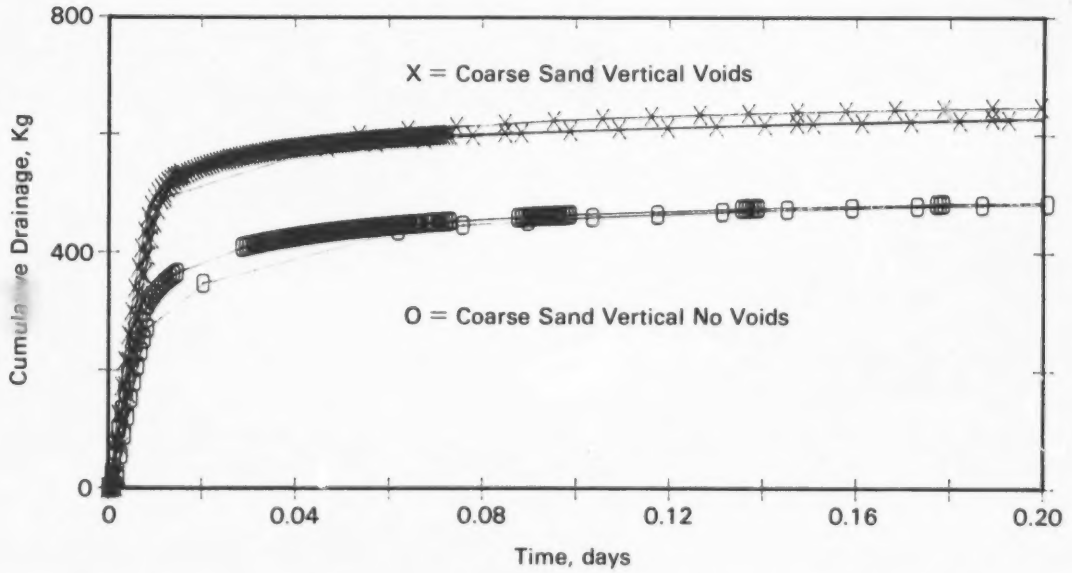


Figure 6.12. Comparison of the effects of voids on cumulative drainage in vertically arranged barrels in sand.

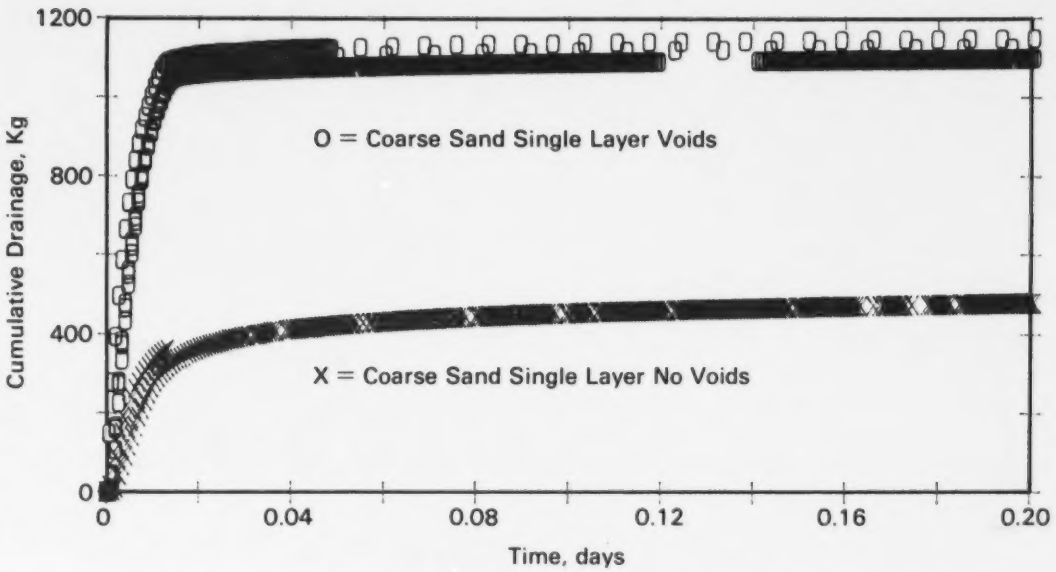


Figure 6.13. Comparison of effects of voids on cumulative drainage in horizontally arranged barrels in sand.

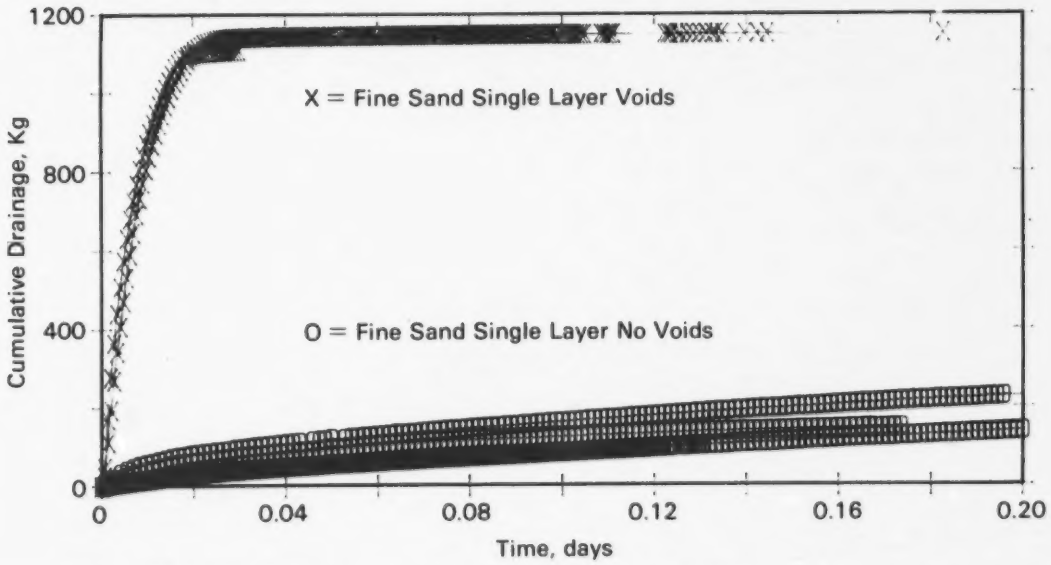


Figure 6.14. Comparison of effects of voids on cumulative drainage in horizontally arranged barrels in loamy sand.

A comparison of drainage between the treatments using sand, single layer, and either with voids or without voids is shown in Figure 6.13. As previously discussed, drainage amounts and tank specific yields are higher in the treatment with voids. The maximum drainage rate is less in the treatment without voids, and drainage continues for a longer time peroid.

Figure 6.14 shows a comparison of drainage between treatments using loamy sand, single layer, and either voids or no voids. Again more drainage is observed in the treatment with voids, resulting in a high specific yield for the tank. The maximum drainage rate for the loamy sand, single layer, and voids treatment of 4.76×10^{-2} cm/s is five times the value of 8.92×10^{-3} cm/s for the loamy sand, single layer, and no voids. Coincidentally, the drainage rate for the loamy sand, single layer, no void treatment takes five times as long (202 min) to drop below 5.46×10^{-4} cm/s as it takes the treatment with loamy sand, single layer, and voids (38 min).

The prediction of leachate production at hazardous waste sites is generally limited by lack of information on the types of hazardous waste and soil hydrologic characteristics. Specific yield analysis has been proposed earlier in this report as a means to estimate the amount of leachate which will drain from a waste site. The results of the physical model studies point to key information that is necessary to adequately estimate leachate production using specific yield.

The most important variable appears to be large void volumes. These can best be estimated from site operator information on the type of barrel arrangement, soil or bulk waste condition during backfilling operations, and the operational efforts made to reduce void volumes. Large voids will increase the specific yield. If the presence of voids is suspected, the specific yield should be increased to account for the void volume when predicting leachate production at a closed waste site. (This increase cannot be calculated in a straightforward manner because it is a function of several interrelated variables and cannot be generalized.) The expected drainage from large voids should be added to the water that will drain from the soil backfill material. The leachate volume from soil drainage is less important for fine-grained soils, which do not drain readily, than for coarse-grained soils, in which a few centimeters change in pressure head causes large changes in water content.

As expected, maximum drainage rates are inversely related to the amount of time required for drainage to cease. Maximum drainage rates for the treatments could be ranked first by the amount of large voids and second by the soil texture. The treatments with large voids drained faster. Void space can be easily eliminated in vertical placement of barrels by backfilling after each layer and using a dry noncohesive soil that will flow in between the barrels. This configuration can help minimize migration of contaminants from leaking barrels when hazardous wastes drain into this dry soil. Finer textured soils with greater water-retention can retain significant quantities of waste liquids. Another possibility would be

pellets of dry, swelling clays that would swell to fill void spaces. If void spaces do exist, subsidence will probably occur first where barrels are arranged vertically. In this arrangement, the soil may become wet and lose its structure and readily fill the void space.

The effect of different soil backfill materials on leachate production can be accounted for using the theoretical principles discussed in Section 3. Briefly, the finer the soil, the lower its saturated conductivity (Figure 3.2) and the greater its water retention at any pressure head (Figure 3.3). Results from the physical models reflect these principles. Finer soil will take considerably longer to drain and as large void volume is decreased, drainage will continue for longer time periods.

Effective use of the specific yield method to predict leachate production requires accurate information on the water retention characteristic of the backfill material and a review of construction details with the site operator. In addition the information needs discussed above should be standardized and recorded during construction of new hazardous waste sites.

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APPENDIX A

CELL VOLUME CALCULATIONS

All dimensions and leachate level values were recorded in feet. The English measurement system was used for calculating the leachate volume. Results were converted to metric and reported in the main body of the text. Table A.1 is equivalent to Table 6.1 in the text. The values used with the following formulas will give the volumes of each subcell.

SUBCELL SATURATED VOLUME CALCULATIONS

In order to calculate the volume of saturated waste in each subcell given the individual monthly leachate levels, h, it is necessary to estimate the volume of each subcell.

The volume of a landfill subcell #45 is shown in Figure A.1. This shape is known as a prismatoid and its volume V, is given by:

$$V = \frac{1}{6} h \, (B_1 + 4M + B_2) \qquad (A.1)$$

Where B_1 is the area of the base (cell floor), M is the area of the midsection, and B_2 is the area of the upper base (the plane defining the leachate level surface) and h is the leachate level.

Since most of the subcells have regular geometry, it is possible to solve B_2 and M in terms of h, the leachate level. B_1 is given by the subcell area at the floor of the landfill. Since the sidewalls of the subcells rise at a rate of 1 ft per 2 ft of horizontal length, the areas of the mid-section (M) and upper base (B_2) can be determined.

For example, subcell #45 is the subcell area at the floor of the landfill. Since the sidewalls of the subcells rise at a rate of 1 ft per 2 ft of horizontal length, the areas of the mid-section (M) and upper base (B_2) can be determined, as shown in Figure A.1. The area B_1 is given by

$$B_1 = l \cdot w = 150 \text{ ft} \times 100 \text{ ft} = 15{,}000 \text{ ft}^2 \qquad (A.2)$$

The area M is given by

$$M = l \cdot w = (150 + h) \cdot (100 + h) = 15{,}000 + 250h + h^2 \text{ ft}^2 \qquad (A.3)$$

TABLE A.1. LEACHATE DATA FROM CELL--MONTHLY MAXIMUM LEACHATE LEVEL

	LEVEL (ft)										VOL (ft3)
	CELL NUMBERS										
DATE	#58	#58A	#59	#59A	#60	#60A	#61	#61A	#62	#62A	TOTAL
SEP 81	23.0	23.2	8.6	7.3	4.7	6.0	6.3	6.2	8.8	22.2	96000
OCT 81	22.7	19.9	9.4	9.7	4.6	4.7	6.3	6.5	18.0	25.5	41100
NOV 81	21.3	21.4	6.2	5.5	4.6	5.1	6.3	5.7	23.2	10.3	49000
DEC 81											39000
JAN 82	22.8	22.0	8.2	7.8	4.7	5.0	5.0	5.2	14.4	23.1	29537
FEB 82	21.4	20.5	9.4	9.6	4.4	4.1	4.7	4.2	12.4	22.1	28975
MAR 82											24000
APR 82											24000
MAY 82	18.2	15.0	5.5	8.4	3.5	5.0	5.6	5.2	24.1	19.8	19192
JUN 82	18.8	14.6	5.8	4.9	4.5	3.2	4.6	5.2	12.6	21.8	15984
JUL 82	18.8	15.0	5.6	5.9	2.8	4.8	4.9	4.6	8.3	19.4	31839
AUG 82	16.4	15.1	2.6	3.7	7.8	12.5	4.0	5.5	6.4	14.9	21631
SEP 82	14.8	14.7	1.5	3.5	1.5	1.7	3.6	5.2	5.1	11.5	15500
OCT 82	13.6	10.8	1.0	2.4	1.1	1.4	2.8	3.2	4.9	9.3	12314
NOV 82	13.4	11.0	1.6	3.7	1.6	1.0	1.7	2.5	3.4	9.0	10091
DEC 82	13.1	11.8	3.8	2.2	1.3	1.1	2.0	2.5	6.7	8.1	9757
JAN 83	12.7	11.6	2.9	1.8	1.4	1.3	2.1	2.2	5.8	6.8	9776

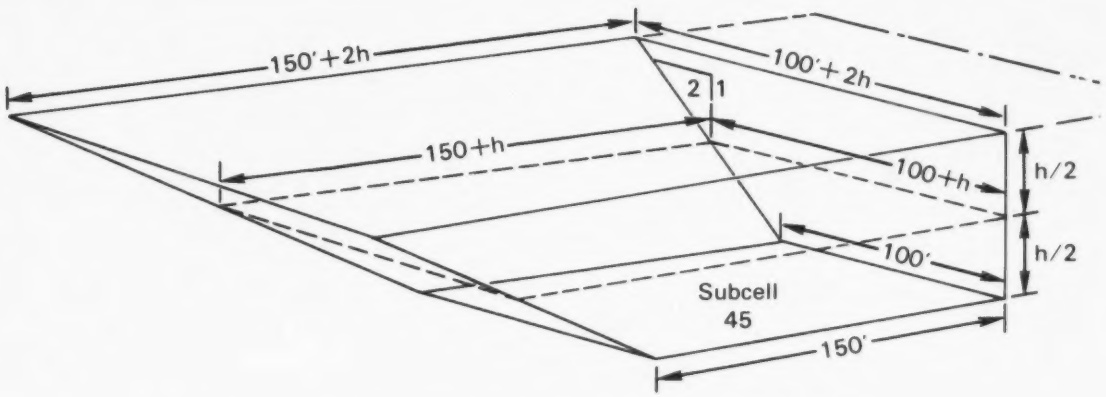

Figure A.1. Schematic of typical subcell construction.

The area B_2 is given by

$$B_2 = l \cdot w = (150 + 2h)\ (100 + 2h) = 15{,}000 + 500h + 4h^2\ ft^2 \qquad (A.4)$$

The total volume of the cell, given a leachate level of h is given

$$V_{45} = \frac{1}{6}\ h\ (15{,}000 + 4\ [15{,}000 + 250h + h^2] + 15{,}000 + 500h + 4h^2)\ \ ft^3$$

The following are the subcell volumes for the cell.

Subcell 58

$B_1 = (220\ ft) \cdot (85\ ft) = 18{,}700\ ft^2$

$M = (220 + 2h) \cdot (85 + h) = 18{,}700 + 390h + 2h^2$

$B_2 = (220 + 4h) \cdot (85 + 2h) = 18{,}700 + 780h + 8h^2$

$$V_{58} = \frac{1}{6}\ h\ [18{,}700 + 4(18{,}700 + 390h + 2h^2) + 18{,}700 + 780h + 8h^2]\ ft^3$$

Subcell 60

$B_1 = (85) \cdot (60) = 5{,}100\ ft^2$

$M = (85)(60 + h) = 5{,}100 + 85h$

$B_2 = (85)\ (60 + 2h) = 5{,}100 + 170h$

$$V_{60} = \frac{1}{6}\ h\ [5{,}100 + 4\ (5{,}100 + 85h) + 5{,}100 + 170h]\ ft^3$$

Subcell 59

Due to the irregular slope of subcell 59, two calculations are necessary. In the first, the combined volume of subcells 59 and 60 is calculated below

$$B_1 = (277 \text{ ft}) \cdot (220 \text{ ft}) = 60{,}900 \text{ ft}^2$$

$$M = (277) \cdot (220 + 2h) = 60{,}900 + 554h$$

$$B_2 = (277)\ (220 + 4h) = 60{,}900 + 1{,}108h$$

$$V_{59+60} = \frac{1}{6} h\ [60{,}900 + 4\ (60{,}900 + 554h) + 60{,}900 + 1{,}108h]\ \text{ft}^3$$

To calculate the volume of subcell 59 alone, the volume of subcell 60 must be subtracted from the above equation

$$V_{59} = V_{59+60} = V_{60}$$

Subcell 61

$$B_1 = (85) \cdot (50) = 4{,}250 \text{ ft}^2$$

$$M = (85 + h) \cdot (50 + h) = 4{,}250 + 135h + h^2 \text{ ft}^2$$

$$B_2 = (85 + 2h) \cdot (50 + 2h) = 4{,}250 + 270h + 4h^2 \text{ ft}^2$$

$$V_{61} = \frac{1}{6} h\ [4{,}250 + 4\ (4{,}250 + 135h + h^2) + 4{,}250 + 270h + 4h^2]\ \text{ft}^3$$

Subcell 62

$$B_1 = (85 \text{ ft}) \cdot (170 \text{ ft}) = 14{,}450 \text{ ft}^2$$

$$M = (85 + h) \cdot (170 + h) = 14{,}450 + 255h + h^2 \text{ ft}^2$$

$$B_2 = (85 + 2h) \cdot (170 + 2h) = 14{,}450 + 510h + 4h^2 \text{ ft}^2$$

APPENDIX B

SOIL CHARACTERIZATION DATA

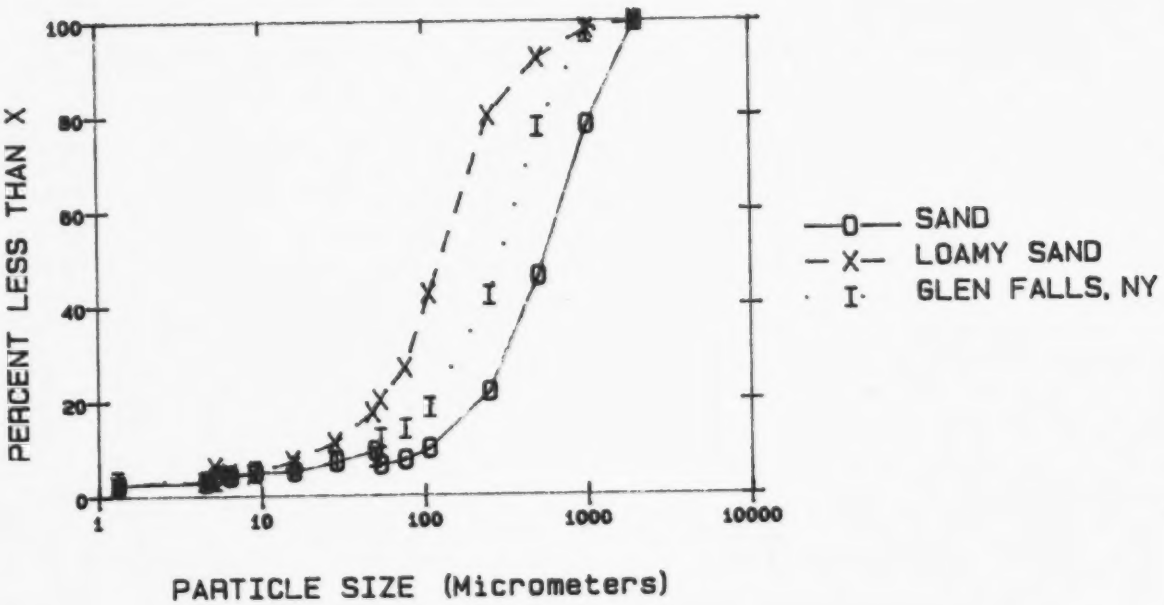

Figure B.1. Particle size distribution for soils used in this study.

TABLE B.1. SATURATED HYDRAULIC CONDUCTIVITY FOR SOILS USED IN THIS STUDY

Sand	6.72×10^{-3} cm/s
Loamy Sand	3.03×10^{-3} cm/s
Glen Falls	5.40×10^{-3} cm/s

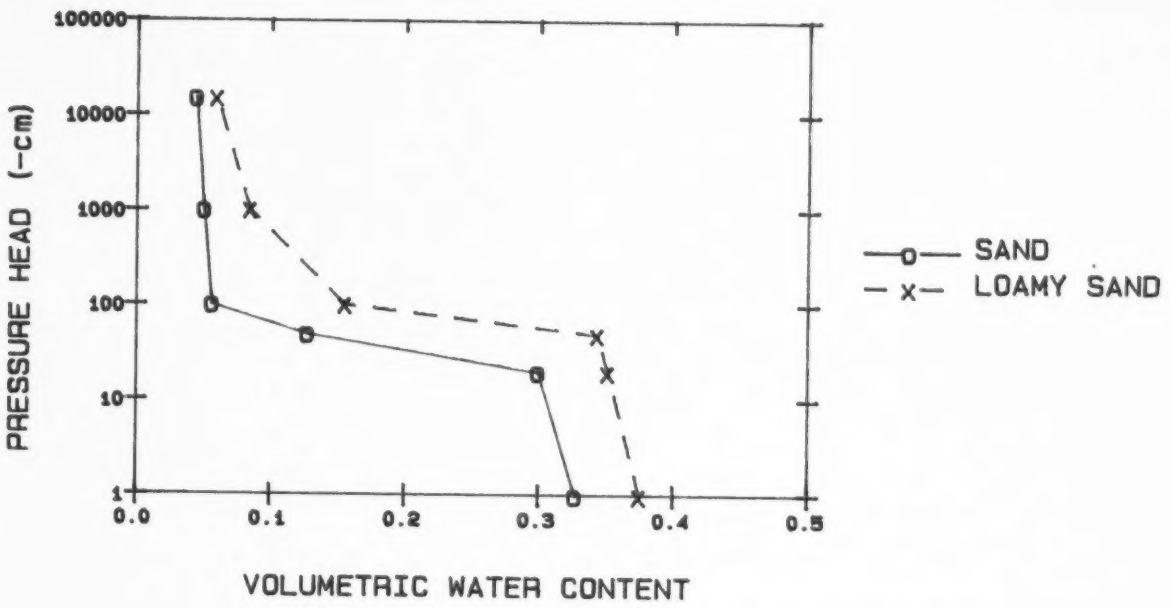

Figure B.2. Water retention for soils used in this study.